

Space Chemistry

Mir Publishers

Moscow



L. Nikolaev



Л. А. Николаев
ХИМИЯ КОСМОСА

Издательство
«Просвещение»
Москва

Space Chemistry

L. NIKOLAEV

Translated from the Russian by
Y. NADLER

Mir Publishers
Moscow

The Greek Alphabet

A α	Alpha	I ι	Iota	P ρ	Rho
B β	Beta	K κ	Kappa	Σ σ	Sigma
Γ γ	Gamma	Λ λ	Lambda	T τ	Tau
Δ δ	Delta	Μ μ	Mu	Υ υ	Upsilon
E ε	Epsilon	N ν	Nu	Φ φ	Phi
Z ζ	Zeta	Ξ ξ	Xi	X χ	Chi
H η	Eta	O ο	Omicron	Ψ ψ	Psi
Θ θ	Theta	Π π	Pi	Ω ω	Omega

На английском языке

First published 1976
Revised from the 1974
Russian edition

© English translation,
Mir Publishers, 1976

CONTENTS

From the Author	7
Chapter I. Research Methods Used in Space Chemistry	12
1. Light Rays and Chemical Composition	12
2. "Optical Specifications" of an Atom	16
3. Cosmic Matter on the Earth	24
4. Analytical Procedures and Techniques	29
Chapter II. Chemical Composition of Celestial Bodies. The Solar System	37
1. Meteorites	37
2. Chemistry of the Solar System . . .	53
3. The Sun and Planets of the Solar System	56
4. The Planets	65
Chapter III. Scope of Earth and Space Chemistry	94
1. General	94
2. What Happens to Matter at High Pressure	97
3. What Happens to Matter at High Temperatures	100
4. Plasma State of Matter	103
Chapter IV. The World of Stars	107
1. Brightness and Luminosity of Stars	107
2. The Hertzsprung-Russell (HR) Diagram and Stellar Evolution	108
3. Chemical Composition of Stars	112
4. Stellar Atmospheres. Light and Gravitation	120
5. Novae	123
6. Supernovae	126
7. Comets	127

Chapter V. Nuclear Reactions and Sources of Stellar Energy	129
1. Constituents of the Atomic Nucleus	129
2. Properties of Some Elementary Particles	132
3. Nuclear Reactions	135
4. Nuclear Energy Sources	136
5. Types of Nuclear Reactions	140
6. Sources of Solar Energy	145
Chapter VI. Evolution of Stars and Synthesis of Elements	151
1. Stages in the Life History of Stars	151
2. The Most Important Nuclear Reactions in Stars	162
3. Interstellar Matter	166
4. Possibility of Formation of Organic Compounds Due to Action of Protons in Solar and Cosmic Radiation	168
5. Chemistry and Cosmology	169
Chapter VII. Primary Synthesis of Organic Compounds	174
1. Physical Factors which Affect Synthesis	174
2. Action of Light on Matter	176
3. Relative Role of Various Energy Sources in Synthesis of Primary Organic Compounds	181
4. Principal Types of Chemical Processes in Space	190
Index	193

Space chemistry is a science of the near future. Rapid progress in the field of chemical research of the planets, stars and nebulae has resulted from the development and application of such sophisticated chemical and physical research techniques as ultraviolet, infrared and radio spectroscopy, as well as the study of X-ray radiation and the magnetic fields of distant celestial bodies.

At the present time much of the data obtained has been verified. The manned space flights and the flights of automatic interplanetary stations have opened the way for the direct analysis of the chemical composition of the planets and the study of the interstellar medium under conditions that have heretofore been impossible. The number of hypotheses and assumptions still remaining in space chemistry is constantly decreasing, while the general picture of element synthesis in the interior of stars and the close connection between the evolution of stars and the chemical processes that occur in them are becoming more clearly defined.

The practical application of space chemistry is of no mean significance: the precise knowledge of the conditions of future space flights, the study of the effect of solar activity on the state of the Earth's atmosphere and the health of its inhabitants—all this

demands an understanding of the chemical processes occurring in outer space.

Near-Earth outer space is gradually being occupied by satellites orbiting our planet. Each year their number is considerably growing and the problems solved

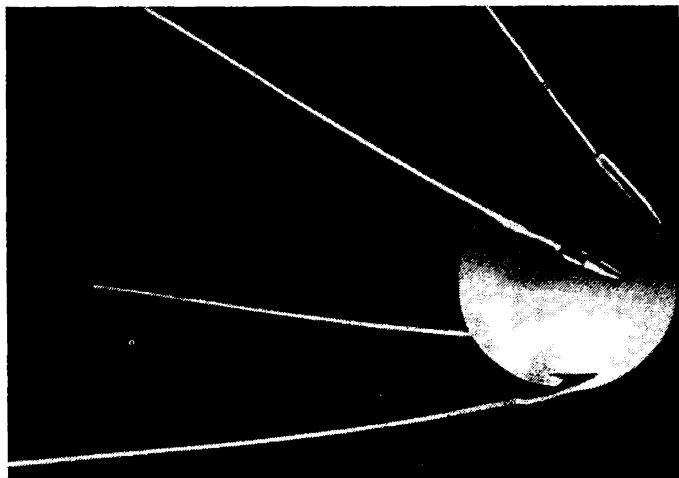


Fig. 1. First Soviet sputnik

with their aid are becoming more complex and varied. Long-range weather forecasts are now made on data provided by meteorological satellites. Highly valuable astronomical information can be obtained by flying observatories. It should be borne in mind that the principal obstacle in the development of Earth astronomy is all kinds of disturbances created by the atmosphere which is in constant motion, always agitated, often misty and cloudy. K. E. Tsiolkovsky dreamt of small "ethereal communities", prototypes of modern

and future space orbital stations. Such stations will be equipped with scientific laboratories, intermediate cosmodromes, perhaps they will carry power plants and even whole factories giving off their wastes far out into space, thus protecting the Earth's atmosphere and surface from pollution.

The creation of high-capacity power plants and factories far from the Earth may seem at first sight to be inexpedient. Why should factories and plants be built so far from the consumers and why should such transport expenditures be incurred? This is, however, no laughing matter as it may appear at a superficial glance. As a matter of fact industrial development on our planet has already reached such dimensions that it is necessary to take into consideration not only wastes but the influence of industry on the world's thermal and chemical conditions. The concentration of carbon dioxide in the Earth's atmosphere is continuously growing and if no measures are taken, in one or two centuries it will become dangerous—our globe will resemble a room filled with cigarette smoke that is in bad need of thorough ventilation. Moreover, the continuous liberation of heat as a result of the activity of millions of plants has already noticeably heightened the mean temperature on the Earth. The amount of energy evolved is so great that very soon (probably in a hundred years) mankind will be receiving as much energy in this way as it does from the Sun. Overheating is inevitable and the consequences may be undesirable. That is why the organization of industry in outer space is quite rational and, judging from available data, quite feasible. This is no longer fantasy, but rather a difficult scientific and technological problem that can, however, be solved.

The conquest of near-Earth space and, all the more so, far-distant space flights demand knowledge of com-

plex chemical and physical factors. As yet science is only embarking on this new path and cannot, by far, foresee all that may be met on it; but the chemical "surprises" encountered will undoubtedly be diverse and complex.

The analysis of soil samples delivered from the Moon by Soviet interplanetary stations showed that lunar rocks contain iron that is practically resistant to oxidation. To the chemist this is an unexpected surprise which requires special study.

The astronauts of the *Apollo* expedition on landing on the Moon discovered that the metal of the spacecraft *Surveyor* that had descended earlier on the Moon had become brittle and crumbled easily due to the action of cosmic radiation on it. Outer space is full of a great number of riddles and the more man knows about the chemistry and physics of the planets, stars and interstellar spaces, the easier it will be for future generations to solve them.

Earth science, of course, has grounds to be proud of its achievements and its knowledge of outer space, but in the course of analysing the state and properties of celestial bodies it has become clear that there are somethings that have to be perfected and supplemented and other things that can be verified on such a scale that is simply impossible on the Earth. New possibilities have even come to mathematics: it has now become possible to answer the question whether the geometry of Euclid or that of Lobachevsky-Riemann should be applied in studying outer space; the fundamental theories of physics (e. g., Einstein's theory of relativity) are being tested in space "proving grounds"; new branches of knowledge (e.g., astrophysics) have sprung up; studies are being made of the laws governing plasma processes at temperatures of millions and billions of degrees, etc. This means that outer space,

on becoming the object of research, has influenced the development of all the branches of natural science.

A characteristic feature of the theory of the evolution of interstellar matter, stars and other cosmic processes is that it is based on the acknowledgement of the deep and inseparable connection between the physical and chemical aspects of these processes. Often the reason for the change in the physical state of a star cannot be understood without investigating the chemical side of the change. On the other hand, the possibility of chemical, and, especially, nuclear-chemical reactions occurring, in a great many cases is determined by physical factors: temperature, gravitational force, magnetic fields, etc. For this reason when studying outer space, chemistry cannot be separated from physics; it would be more correct to speak of space physical chemistry (or chemical physics) than of chemistry in the strict sense of the term. We must constantly turn our attention to the physical conditions under which the reactions proceed although the purely chemical data in this field is very interesting and diverse.

In this small book an attempt has been made to set forth the distinguishing features of the chemical phenomena characteristic of outer space. We have allotted special attention to the theoretical and experimental methods of investigation of space, avoiding however, repetition of the material contained in school courses of physics and chemistry. At the same time, striving to make the book as popular as possible, we confined ourselves only to the most essential information concerning the nature of the atomic nucleus, the laws of nuclear energetics, the origin of various kinds of spectra, etc. The scope of the knowledge of physics, chemistry and mathematics given at our secondary schools is quite sufficient for understanding this book.

Research Methods Used in Space Chemistry

1. LIGHT RAYS AND CHEMICAL COMPOSITION

At the very first acquaintance with chemistry and chemical analysis it becomes clear that in order to ascertain the composition of a substance it is necessary, first of all, to have the appropriate quantity of the substance. The chemist treats the material under test with certain reagents and observes the changes that occur (the appearance of precipitates, colour, gases, etc.). Not so long ago, the study of meteorites was the only means of investigating cosmic matter by chemical analysis.

Now when the Earth's nearest neighbour, the Moon, has been explored by the Soviet *Luna* automatic interplanetary stations, *Lunokhod* and the American *Apollo* expeditions, and samples of lunar rocks have been delivered to the Earth, direct chemical analysis of celestial bodies is a matter that can be spoken of with certainty. This, naturally, is the most reliable source of information.

The investigations of planets with the aid of automatic interplanetary stations are undoubtedly of great importance. Soviet stations that landed on Venus and Mars have communicated from there important data on the composition of the atmosphere of these planets. The American interplanetary station *Pioneer-11* took pictures of the surface of Jupiter at a distance of

42,000 km. However, it should be borne in mind that the nearest star (Alpha Centauri) is 4.2 light-years from us, i.e., light travelling from it at a speed of 300,000 km per second reaches us in 4.2 years! Of course, there are no grounds to expect that such far-distant space flights will be made very soon. But the means, by which the automatic stations flying to the Moon or Venus transmit the necessary data to the Earth and by which they receive commands from the Earth, is also used by the stars, including the Sun, to tell us about themselves. The means referred to is light rays; the study of light rays is called *spectral analysis*.

The Sun's rays bringing light and life to the Earth can provide data on the chemical composition of stars and their physical state: temperature, motion of hot particles and energy of nuclear reactions. However, all this can be found out only if you can read the elusive, seemingly weightless and non-material light ray.

In ancient times people prayed at dawn, greeting sunlight; but thousands of years passed before the language of sun rays was understood. The rainbow was not only admired for the beautiful spectacle it presented but it made men wonder why instead of "white" light there suddenly appeared a series of bright coloured bands. Already in the XIII century, correct surmises as to the nature of the rainbow were made. Grossetst and Vitelo Silezski related this phenomenon to the diffraction of light in drops of rain water, and in 1666 the great Newton, with the aid of a glass prism, dispersed sunlight into its constituent coloured rays. Scientists began to study the spectrum thus obtained. The glowing surface of the Sun sends to the Earth rays of all colours which on blending produce white light. I. Fraunhofer and G. Kirchhoff established the presence of dark lines in the continuous spectrum

of the Sun. They explained these dark bands correctly. The Sun's atmosphere contains definite elements (sodium, iron, calcium and other elements) and their atoms absorb from the light radiated by the Sun part of the rays, namely those which are characteristic of

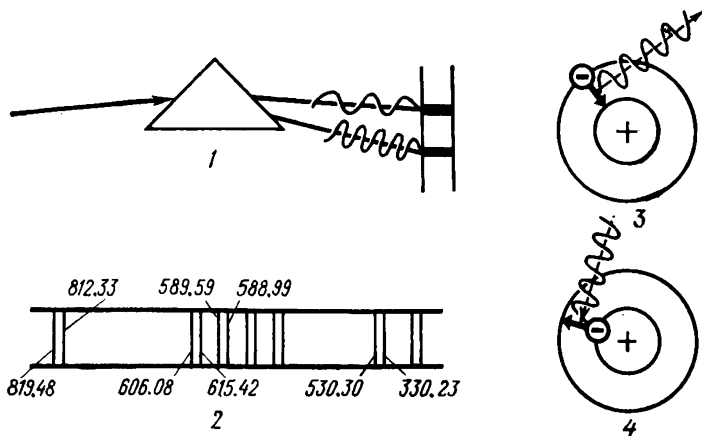


Fig. 2.

Left: 1 — formation of spectrum; the prism deflects rays with short wavelengths to a greater degree and therefore the beam of light is dispersed on passing through the prism; 2 — emission spectrum of sodium (wavelength in nanometres). Right: 3 — light is radiated by the atom on transition of an electron from a distant orbit to a nearer one; 4 — light is absorbed by the atom and the electron passes to the excited state

their own radiation (Fig. 2, 1 and 2). Consequently, what elements are found on the Sun can be determined by the arrangement of the dark lines. Thus, the first steps were taken in the interpretation of the language of light. Yet the philosopher A. Kont asserted that man would never know what the stars were composed of; that was about 140 years ago. In a short period of time the science of space chemistry has gone a very long way.

In many cases the characteristic lines of the emission spectra of various cosmic objects (such as nebulae and stars) can be observed and from their position the chemical nature of the particles that sent the rays into space can be inferred correctly.

Celestial bodies, as is well known, often have a high temperature and for this reason are very suitable objects for spectral analysis. If the temperature is low, it is more difficult to conduct chemical analysis, but in this case it is not altogether hopeless. The beam of light directed onto the surface of any body is partially absorbed and partially reflected. The spectral composition of the reflected ray differs from that of the incident ray; that is why we perceive the colour of things: the leaves of trees seem to be green because the chlorophyll contained in the leaves absorbs red rays from the sunlight while the yellow-green rays are reflected and fall on the retina of the eye of the observer and produce the visual sensation of the green colour. By studying the spectra of reflected rays it is possible to infer the chemical composition of celestial bodies having relatively low temperatures. In this way the first information was obtained about the composition of lunar rocks; of the chemical nature of the surface of Mars¹.

Spectral analysis of emitted and reflected rays can be carried out not only in the region of visible rays but also in the region of long waves which lie beyond the blue end of the spectrum (in the ultraviolet part of it) or beyond the red end (in its infrared part).

Let us familiarize ourselves with certain fundamentals of chemical spectral analysis.

¹ Of course, the presence of a dense atmosphere on the planet (for example, on Venus or Jupiter) prevents the use of spectra of reflected light for studying the surface of planets.

2. "OPTICAL SPECIFICATIONS" OF AN ATOM

The atoms of substances are capable of absorbing and radiating light. If an electron revolving about the nucleus of an atom receives a quantity of energy, it generally passes to an orbit of a larger radius. M. Planck proved that the frequency of vibration ν of the wave of light falling on a given atom is related to the quantity of energy ϵ which the atom absorbed from the light as follows:

$$\epsilon = h\nu$$

where h is Planck's constant equal to 6.62×10^{-27} erg·s.

This signifies that light behaves not only as a wave process but as a flow of small material particles with a quantity of energy or quantum (the word *quantum* is the latin for quantity), also called a *photon*. The electron that has absorbed a quantum of energy and subsequently passed to an orbit farther from the nucleus is now in the excited state. It persists in this state for a very short period of time. As a rule, it jumps back to the orbit of the ground state in millionth parts of a second and the absorbed quantum is radiated in the form of an electromagnetic wave of the same length and frequency of vibration as the original wave.

It was established by N. Bohr, an outstanding Danish researcher in the field of atomic physics, that electrons in an atom can revolve without losing energy only in certain "permitted" orbits whose radius can be calculated.

Bohr's theory was only the first step in the field of atomic physics. In 1924, de Broglie (France) came to the conclusion that the combination of wave and corpuscular properties is characteristic of all *elementary particles* in the atom (electron, proton, neutron, etc.), and experimental data and further theoretical develop-

ment have confirmed de Broglie's views. The dual nature of the behaviour of the objects of atomic physics resulted in the impossibility of simultaneously determining the position of an electron and its momentum with certainty.

It is possible to calculate with certainty not the values of radii in an atom but only the probability of finding the electron at a given distance from the nucleus of the atom. Each orbit¹ corresponds to a specific energy level in the atom. The transition of electrons between the orbits, i.e., transition from one energy level to another, is accompanied by the radiation or absorption of energy. Energy is radiated or absorbed as light waves, and consequently, each atom can be characterized by the series of light waves, which corresponds to the transition of electrons between the energy levels in a given atom (Fig. 2, 3 and 4).

The term *light wave* applies not only to visible light but to electromagnetic waves in general, including ultraviolet and infrared waves. The length of an electromagnetic wave denoted as λ , the frequency of vibration ν and the velocity of wave propagation c are related as follows:

$$c = \nu\lambda$$

The velocity of propagation of an electromagnetic wave in vacuum is enormous; it is equal to 3×10^{10} cm/s or 300,000 km/s.

The simplest atom, the hydrogen atom, has only one electron. On absorbing energy in any form the electron can rise to one of the higher energy levels; the atom passes over to the excited state. Then follows

¹ Since the concept *orbit* from the point of view of wave mechanics no longer makes any sense, the term *orbital* is often used; it denotes a function with the aid of which the energy level of electrons is calculated.

the reverse transition and the atom becomes the source of radiation. The atom radiates a specific wave depending on the level to which the electron passes. If from the higher level the electron returns to the ground orbit at once, there will be given off a quantum of relatively high energy and hence, according to Planck's formula, of a high frequency, i.e., a short wavelength. The waves produce in the spectrum a series of lines located in the ultraviolet region. They cannot be seen with the naked eye but can be observed and photographed by special instruments (quartz spectrophotometers and spectrographs). If an electron, as is often the case, does not return to the ground state at once but passes from various distant orbits to the second one from the nucleus, waves are emitted with wavelengths corresponding to the visible region of the spectrum. When transitions of electrons take place from any far orbit to the third one from the nucleus, a group of waves is emitted that have wavelengths corresponding to infrared waves. They can be detected by the heating up of the junction of a thermocouple placed opposite the light waves or with the aid of specially treated plates sensitive to infrared waves.

The spectral lines obtained under different conditions of excitement of an atom completely characterize the atom, i.e., constitute its "optical specifications". If the wavelengths characteristic of a given atom under Earth conditions are known, it is possible to conjecture whether one or another element is present in a star from its spectrum, though mistakes are sometimes possible. The conditions on the stars are so extraordinary for Earth laboratories that there were instances when the spectral lines found on studying star radiations were attributed to new elements although they were, in reality, lines emitted by known substances under conditions that could not be simulated on the

Earth. At the present time, however, the probability of such mistakes is small, and spectral analysis is one of the mightiest means of investigating the chemical composition of celestial bodies.

In addition to information about the chemical composition of distant stars, spectral analysis can also give an idea of the temperature of stars. Very high temperatures correspond to the formation of plasma. In such a state the atoms are free of outer electrons, and the spectrum shows only lines of hydrogen and ionized helium. At lower temperatures atoms of heavier elements are formed and then compounds of the type of stable oxides. Thus, the temperature of the source of radiation can be inferred from the general character of the spectrum.

There exists a dependence between the temperature of a heated body and the wavelength on which most of the energy is radiated. Hence, the temperature of a source emitting a continuous spectrum can be surmised by studying the energy distribution in accordance with the wavelengths of the radiated light. It was precisely the investigation of the spectrum that enabled scientists to correct the mistake made when the temperature of the planet Jupiter was discussed. It was supposed that Jupiter is a red-hot mass: the bright stripes and spots on the surface of its vast atmosphere gave rise to this supposition. However, the analysis of the radiation of this giant planet showed that Jupiter shines only by reflected sunlight; its own small radiation corresponds to a relatively low temperature of 120-170°C.

Very interesting data on the composition of atmospheres was obtained by investigating absorption spectra. If an atmosphere contains molecules of a certain compound, these molecules will absorb the radiation emanating from the surface of the given planet and

dark bands can be seen in the spectrum that are characteristic of the molecule as a whole (not of individual atoms). Molecules also have "optical specifications" which are more complex and more difficult to interpret than those of atoms.

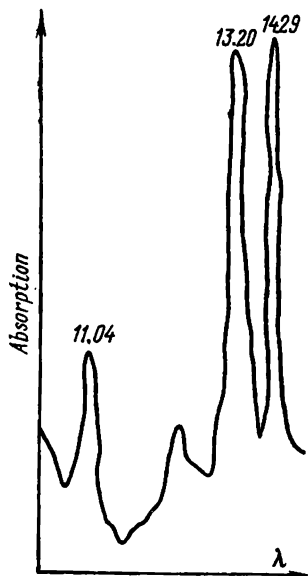


Fig. 3. Absorption spectrum of water in the infrared region (wavelength in μm)

Fig. 3 shows the wavelengths characteristic of the absorption spectrum of water.

Spectral analysis has revealed the presence of carbon dioxide and a very small quantity of oxygen in the atmosphere of Venus. Now when thanks to Soviet automatic interplanetary stations we have exact data that the atmosphere of the "evening and morning star" really consists mainly of carbon dioxide, CO_2 , it can be said that spectral analysis has passed the test, and, consequently, the information obtained by this method pertaining to other planets and stars is quite trustworthy.

Spectral analysis is one of the most effective means of investigation in space chemistry. It permits discovering, at great distances from measuring instruments, the presence not only of atoms and ions but also of more complex particles (radicals and molecules) possessing characteristic spectra. The analysis of spectra has made it possible to obtain a precise idea of the physical state of an object, its temperature, the con-

centration of various substances in it and even of the character of the motion of celestial bodies.

Let it be assumed that for some reason the electromagnetic wave of an atom is rapidly receding from us. How will the position of the spectral line change in this case? Less waves will get into the objective of the spectroscope per unit time than in the case of a stationary distance between the instrument and the wave source: the wavelength seems to increase and, accordingly, the frequency to decrease; the spectral line shifts to the red end of the spectrum, i.e., in the direction of longer waves. The velocity of the radiating body can be estimated from the red shift in the position of the lines in their spectra. This phenomenon is called the *Doppler effect*. Hence, spectral analysis can be used not only for drawing conclusions about the chemical composition of celestial bodies but also about their motion.

Recent years have brought important discoveries in radio spectroscopy, i.e., in the field which studies electromagnetic oscillations of relatively low frequency. It has been established that there are regions in space that emit radio waves; some of the sources do so very intensively. It has been found that in a number of cases emission is of a periodic nature (pulsating stars). The study of radio emission in space is undoubtedly one of the most interesting and promising branches of astrophysics. Astronomers are actively using radio waves for examining the depths of outer space.

The investigation of reflected radio waves has opened the way for extensive study of the planets. The character of the reflection of radio waves is connected with the structure of a surface. Radio waves are reflected from a smooth surface differently than from a rough surface. Consequently, by studying electromagnetic waves it is possible not only to determine

the composition of celestial bodies but even to visualize the physical structure of its outer layers.

A reflected radio wave informs the physicist about the magnitude of the dielectric constant of the substance from which it is reflected. The dielectric constant shows how many times the force of attraction between two charges is smaller in a given medium than it is in vacuum. Thus, for example, if a force of 162 dynes acts between two charges in vacuum, in water this force will be 81 times smaller and will hardly reach 2 dynes. A specific dielectric constant is characteristic of every individual substance (sand, marble, water, benzene, ice, etc.). That is why the magnitude of this physical constant can be used to make well-founded assumptions concerning the composition of the surface reflected. Thus, the value of the dielectric constant, which is equal to 3.75, obtained for Venus speaks in favour of the assumption that this planet has a sandy or rocky surface.

Of especial interest was the study of waves of a length of 21 cm. Such waves are emitted by the most widespread element in the universe, hydrogen, when a change occurs in the state of the electron associated with the self-rotation of this particle.

The fact is that the nucleus and electron in the hydrogen atom are characterized by an angular momentum; so that for the sake of simplicity the hydrogen atom can be pictured as consisting of two tops, the nucleus and electron, each of which rotates on its own axis and about the common centre of gravity (Fig. 4).

The quantity of energy in the atom depends on whether the "tops" are rotating on their axes in the same direction or in opposite directions. For this reason the transition of an atom from one state to another is accompanied by the radiation of electromagnetic

waves 21 cm in length. The hydrogen atom very rarely undergoes such a transition; millions of years can pass before the direction of rotation changes but the number of hydrogen atoms in space is so great that it is possible to study the radiation of a wavelength of 21 cm. The results of investigations have provided data from which the density of hydrogen in different

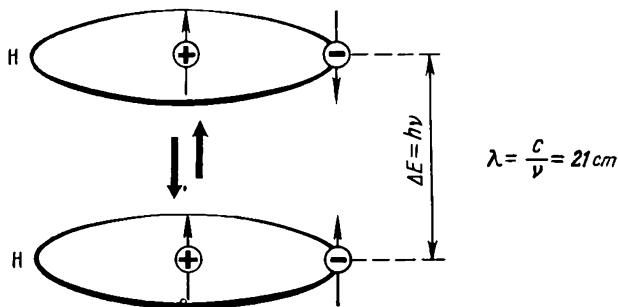


Fig. 4. Two states of the hydrogen atom. Transitions between them are accompanied by radiation or absorption of waves having a length of 21 cm

regions of space can be inferred. Of great promise are the investigations of short-wave radiation of the type of X-rays: this radiation affords evidence of powerful nuclear and electronic processes that break out in the depth of outer space. From there scientists are continually receiving information recorded in the language of frequency and their task, which is by no means an easy one, is to interpret these messages. All the information obtained on studying the data of spectral analyses shows that in outer space there are no elements that are unknown to man; but in celestial bodies the elements familiar to us are often under conditions that cannot be simulated on the Earth.

3. COSMIC MATTER ON THE EARTH

The Earth, enveloped by the atmosphere, rushes through space, and although the atmosphere appreciably weakens the action of radiation, it is not impenetrable to some solid particles which can be met with on the way. Even when these solid particles are strongly heated because of friction against air and are completely converted to vapours, all the same the products of their conversion sooner or later will reach the Earth.

As a matter of fact, solid bodies of all possible sizes from the fine particles of cosmic dust to large meteorites with a mass of hundreds of kilograms and even several tons fall on the Earth.

Cosmic dust slowly settles down on the surface of the Earth and recently, thanks to data from artificial Earth satellites, it has become possible to determine the daily fallout of this dust. It proved to be enormous: daily our planet receives up to 20,000 tons of cosmic matter. The composition of the Earth's surface cannot differ essentially from that of the cloud of rarefied dust through which all the celestial bodies of our solar system have been moving for billions of years (see below the theory of O. Yu. Shmidt). It is of interest to know that the fallout of dust varies. In 1938, such a large cloud of dust invaded the Earth's atmosphere that in the vast northern regions of Siberia the intensity of daylight was markedly reduced.

The Earth not only receives matter but loses it as well. Part of the gases and water vapour in the atmosphere are carried off into space. It may well be that in a remote geological era there was more water on the Earth and the level of the World's ocean was considerably higher. Thus, the Earth and outer space are constantly exchanging energy and matter, i.e., together they constitute a dynamic system.

The sizes of meteorites vary over a wide range. In its motion the Earth periodically crosses the orbit of a meteor swarm. Between Mars and Jupiter there are a great many (more than 3000) small fragments of celestial bodies which revolve around the Sun but sometimes deviate from their orbits and, being drawn into the region of gravitational attraction of our planet, fall onto it. Small fragments of a mass equal to a fraction of a gram (meteoritic particles) burn up in the atmosphere, leaving a luminous trail of "a falling star" behind them, while larger ones (meteorites) can reach the Earth's surface.

The appearance of meteorites was always unexpected and the light and sound effects, often very violent, that accompanied their fall aroused fear and even panic. Many vivid descriptions of terrible events recorded in ancient documents and chronicles have come to our days. In the Nikonov annals of the year 1421 it is said of a meteorite that fell in the Great Novgorod: "... rain and hail and stones fell from the clouds to the Earth... and people were hardly able to recover from their fright".

In 1162, during a meteorite shower in the vicinity of the Kirillo-Belozersky monastery many small stones fell to the ground. An eye-witness wrote: "the ground shook, mansions tottered and many people in their terror fell to the earth. And then small and large stones fell with great violence"¹.

These observations evidently pertain to stony meteorites. Iron meteorites are encountered more rarely, however, they are easier to find after they have fallen. Iron meteorites were sometimes used for making weapons. Meteoritic iron supplied the inhabitants of

¹ B. Vorontsov-Velyaminov. *Ocherki o vseleynoy* (An Essay on the Universe). Gosteoretizdat, Moscow, 1951.

Greenland with the means for making knives and other instruments. Meteorites were the sole source of metal because the layer of ice and snow on the ground there excluded any access to mineral ores. In 1621, in Lagor (India), swords, daggers and lances were made from meteoritic iron, though this was very difficult because "celestial iron" can be wrought (hammered into shape) only in the cold state.

Strange as it may seem the very fact that meteorites do fall was doubted by scientists for a long time and even at the end of the XVIII century (1790) when discussing reports on a observed meteorite, the members of the French academy, including the famous chemist A. Lavoisier, came to the conclusion that it was physically impossible for stones to fall from the sky. This paradoxical situation can partly be attributed, probably, to the fact that the remnants of small meteorites sometimes differ in appearance so little from terrestrial rocks that they do not attract attention. The first official report stating that two "pieces of iron", i.e., iron meteorites, fell down from the sky dates to 1751 (according to B. Vorontsov-Velyaminov); it is an episcopal record of an event that occurred in Grashin (Yugoslavia), on May 26, 1751. Twenty years later in 1772, in Siberia, Academician Pallas discovered an iron-stony meteorite previously found by the Cossak Medvedev in the 40s; it weighed 700 kg. This meteorite went down in scientific history under the name of "Pallas iron" and served as the basis for the book by E. Chladny printed in 1794 in which the author proved that stones can fall from the sky despite the doubts of sceptics. An important feature of the investigations of this scientist was the acknowledgement of the cosmic origin of these mysterious stones. Still earlier (in 1754) the idea of the extraterrestrial origin of meteorites was mentioned by Stepling, the Czech

investigator-astronomer. In 1803, the same conclusions were drawn by the French Academy of Sciences but all doubt was dispelled only after a meteorite shower consisting of about 3000 small meteorites fell on the city of L'Aigle.

Gradually meteorites began to attract the attention of chemists, geologists and even travellers who found traces of their falls in various regions of the globe and sometimes fragments of large bodies breaking up or exploding at the end of their travel in space. In 1897, Peary found an enormous iron meteorite (33 tons) in the ice blocks of Greenland; in Hoba (South-West Africa), a 60-ton giant meteorite was found containing iron and nickel (16 per cent); in 1937, near Minsk a meteorite was found with a mass of 188 kg; in Mexico, there is a meteorite weighing more than 24 tons, left on the spot where it fell, etc.

One of the meteorites excavated in Quaternary deposits in Argentina at a depth of 6 metres was, apparently, the cause of the death of a megatherium whose bones were found at the very spot where the meteorite fell. Some celestial wanderers — stones falling on the Earth's surface — had colossal dimensions. Traces of a visit of one of these meteorites that struck the ground can be found in Arizona where on the surface of the lime-sandy plateau there is a large crater, the Canyon Diablo, having the shape of a funnel 1.2 km in diameter. The depth of the crater is 180 metres; it is surrounded by a wall 45 metres high. The violence of the explosion can be inferred from the fact that a slab of stone almost half a kilometre long was stood up vertically by the explosion and a number of fragments of cliff rock of a mass up to 700 tons was scattered at a distance of 10 km. It is believed that the meteorite probably went deeply into the ground, but repeated attempts to reach it

were unsuccessful, although at a depth of 300 metres the borers were broken on striking some hard material. It is supposed that the Arizona meteorite fell onto the Earth 5000 years ago.

In 1908, a meteorite of gigantic size fell and exploded in the region of Podkamennaya Tunguska. Flying above the Earth in the North-Eastern direction it radiated such a bright light that it outshone the Sun. Approaching the Earth's surface at a rate of tens of kilometres per second it exploded in the taiga (vast Siberian coniferous forest) and formed numerous craters in the zone of explosion. The sound produced by the explosion was heard at a distance of 700 km. At a distance of 60 km from the spot where the explosion occurred the effect of the blast was devastating. The woodland in that region was burnt down and felled in an area with a diameter of about 25 km. The explosion wave went round the globe twice and was registered in Germany and the United States. The meteorite, apparently, was broken up into very small fragments and its main mass vaporized at the moment of explosion; no fragments have ever been found.

In 1947, in the vicinity of Sikhote-Alin an enormous meteorite fell to the Earth leaving a bright luminous trail behind it, which could be seen at a distance of 300 km. The expeditions that worked at the site of the explosion (F. Shipulin, V. Fesekov, E. Krinov and others) found 106 craters and thousands of fragments. The total mass of the meteorite shower (according to B. Vorontsov-Velyaminov) was approximately 100 tons.

In our times all meteorites are carefully examined and registered, and the science of meteorites (known as meteoritics) is a wide and well developed branch of astrophysics.

The chemical analysis of meteorites is simple enough when compounds whose content in celestial bodies is relatively large are concerned; the analysis of substance whose concentration is very small is much more difficult.

4. ANALYTICAL PROCEDURES AND TECHNIQUES

Qualitative and quantitative chemical analysis is carried out by different methods depending on the quantity of the substance at hand, its nature and also the accuracy required. Although for many commercial products the quantitative determination of impurities to the nearest 10^{-3} per cent is often quite adequate, in other cases the materials used in modern technology demand an accuracy of 10^{-6} per cent and even 10^{-8} per cent. When investigating meteoritic substances the accuracy must be even greater. Sometimes theoretical deductions of enormous importance for the progress of space science depend on the correct estimation of the content of a certain compound.

Therefore the chemical methods of meteoritic analysis are supplemented by physico-chemical methods of analysis. If the analyst is provided with a piece of stony meteorite of sufficient size, he should begin with chemical analysis. It can be assumed at the very start, for example, that the meteorite contains silicon dioxide (SiO_2). But prior to proceeding with quantitative analysis, preliminary qualitative tests should be made to obtain an idea of the nature of the substance under test. In order to determine the content of silicic acid, a weighed portion of the material is treated with perchloric acid solution (HClO_4), then boiled to dissolve the metal compounds and the precipitated acid is filtered, washed, dried and weighed.

To check the accuracy of the determination, the silicic acid precipitate is treated with hydrofluoric acid whereupon the silicon is converted to silicon tetrafluoride; on heating, the tetrafluoride vapourizes and the original content of silicic acid can be found from the loss in mass. This is a typical procedure in analytical chemistry, tested on hundreds of thousands if not millions of specimens, which gives unerring results.

But the analyst may be faced by another problem. It is supposed that the meteorite contains a complex mixture of organic compounds. The amount of organic matter is very small and the nature of the components and even their number are unknown. Should purely chemical methods be used in this case? It would be taking a chance of losing precious material because we do not know how the components will behave in the process of chemical treatment, heating, drying, etc.

The analyst will try to dissolve the material in an organic solvent or mixture of solvents and will then try physico-chemical methods of analysis. He will probably apply chromatographic or spectral analysis. Chromatography is indeed a marvelous discovery. For hundreds of years people observed how a solution of a mixture of dyes spreads over porous materials, fabrics, paper and how there appear coloured rings and stripes indicating the separation of the dyes. To observe this phenomenon, it is enough to mix inks of different colours and then to apply a drop of the resulting solution on filter paper, even on a blotter: the individual dyes are separated and instead of a monochromatic spot we'll obtain concentric rings of different colours. It did not occur to anybody that here was the key to the solution of very complex problems of analytical chemistry. It required the genius of

M. Tsvet to understand the practical application of this natural separation of a mixture due to the diverse absorbability of organic compounds in a layer of porous material.

A complex mixture of substances, for example, of amino acids dissolved in water is absorbed on a sheet of paper immersed vertically in the solution. Different amino acids rise at different rates, and if the process is discontinued, each acid will reach a different place on the paper. The zones where the acids are concentrated can be expanded out by saturating the sheet of paper with an appropriate solvent and, finally, these zones can be clearly seen if the paper is treated with the organic compound ninhydrin in which all amino acids give compounds that are red-violet in colour.

Now to perform quantitative analysis, the parts of the sheet of paper where individual amino acids have accumulated are cut out, the coloured substance is extracted by a solvent and its content determined, preferably with the aid of a spectrograph. This constitutes the whole analysis. The example of the analysis of a mixture of amino acids is given because such mixtures are the most difficult to analyze by purely chemical methods. The major part of the great progress achieved in our days in the field of the chemistry of proteins and natural complex compounds, the chemistry of transuranium elements, etc. is based on chromatographic analysis. There are various techniques of chromatographic separation. Not only paper is used as the absorbent, but also different carbonates, oxides, starch, etc.

Gas chromatography is used for analyzing volatile substances (gases and vapours). The mixture of gases is passed through a column (a long tube) containing an adsorbent (for example, coal). The layers of adsor-

bent are gradually saturated. At a certain moment at the other end of the column one of the mixture components begins to emerge, the component which is less readily adsorbed and that is followed by a component that is more readily adsorbed, etc.; the mixture is thus separated. The first ("front") layer of the

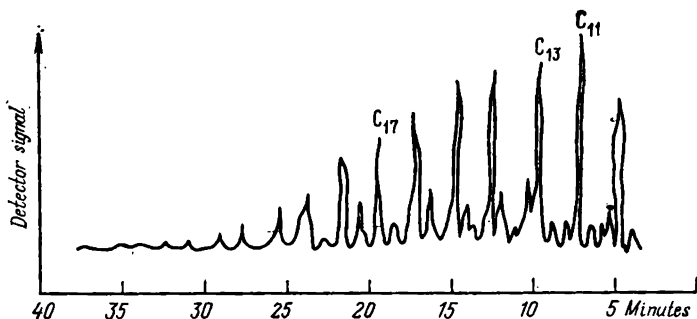


Fig. 5. Typical gas chromatogram: the separation of a mixture of hydrocarbons. Axis of abscissas — time in minutes; axis of ordinates—detector signals indicating the amount of effluent component; C_{17} , C_{13} , C_{11} —the number of carbon atoms in the hydrocarbon molecule

adsorbent can be saturated with the mixture of volatile substances and then the adsorbed components are expelled with the aid of a continuous stream of inert carrier gas. The separation of the components takes place within the layer of adsorbent where adsorption zones of all the components are formed. The components of the mixture emerge from the exit of the column one after another (this method is known as gas chromatography by selective adsorption). The apparatus for such analyses are chromatographs which operate automatically and with a high degree of accuracy (Fig. 5).

Chromatography made possible the analysis of the composition of very rare meteorites of unexplained origin—of carbonaceous chondrites which will be considered below.

Above we have already mentioned the spectrograph, an instrument which can be used very effectively for direct analysis of substances. Let us examine its mode of operation in greater detail. Spectrographs are used to study absorption spectra. The point is that in order to obtain emission spectra it is necessary to heat the substance under test strongly and many complex molecules do not withstand heating. A ray of light on passing through a substance in the pure state or in solution is partially or completely absorbed by it. The reason for this is that the energy of the light waves is spent to change the motion of the constituent parts of the molecule. Waves of long wavelengths from beyond the red end of the spectrum (infrared radiation) are absorbed by certain groups of atoms, for example, OH, NH₂, CH, CO, etc.; each group absorbs radiation of different wavelengths within a narrow range. The absorbed energy is expended to raise the energy level of the atomic nuclei vibrating at a definite frequency. Visible light and ultraviolet radiation carrying large quantities (quanta) of energy transfer the electrons of the molecules to higher levels. Visible and ultraviolet rays can be recorded by various means; in particular, with the aid of photographic plates on which these waves act strongly.

It is convenient to register infrared rays with the help of a thermocouple or bolometer. A thermocouple is a combination of two dissimilar metals in the junction of which a current is generated that is proportional to the amount of energy absorbed. A bolometer consists of a fine blackened platinum wire the resistance of which changes with heat. The infrared rays

heat the wire and the intensity of a wave in the infrared part of the spectrum is inferred from the change in the resistance of the wire.

A beam of light containing various waves is absorbed in a complex molecule by electrons and whole groups of atoms. In accordance with the decrease in the intensity of radiation of one or another wavelength after it has passed through the substance it is possible to determine of what atoms the molecules of the substance are composed and how they are distributed. Sometimes the result obtained can be checked. Let us assume, for example, that after dissolving a portion of carbonaceous chondrite in an organic solvent and determining what waves are absorbed by the solution we come to the conclusion that the solution contains the hydrocarbon naphthalene. To check this let us take a solution containing this hydrocarbon and compare its absorption spectrum with that observed in the meteorite extract. Identical spectra are the best proof that the composition of the substance was correctly inferred. The instruments used for investigating such absorption spectra are called spectrographs. They are often designed so that rays of all wavelengths may pass successively through the substance under test, and the instrument automatically records the degree of absorption in the given substance of each wave (actually in a very narrow range of wavelengths). As a result, a curve is obtained on which the wavelength in nanometres or angstroms ($1\text{\AA} = 0.1\text{ nm} = 10^{-8}\text{ cm}$) is plotted on the axis of abscissas and the value that characterizes absorption (optical density, i.e., the logarithm of the ratio of the intensity of incident light to the intensity of the light that passes through the solution; optical density is directly proportional to the concentration of the substance), on the axis of ordinates. Since absorption is proportional to the concentra-

tion of a substance, the content of a given constituent in the mixture can be determined quantitatively as well as qualitatively.

For rapid analysis of the elements found in iron meteorites, use can be made of instruments in which

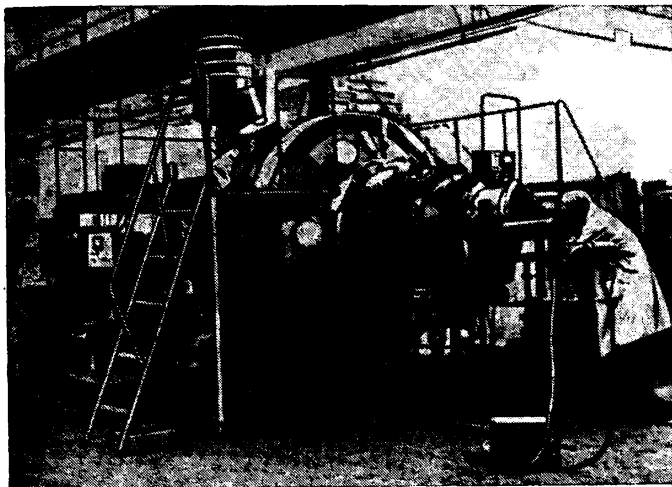


Fig. 6. General view of apparatus for analyzing lunar soil in vacuum

the substance under test is heated to a very high temperature at which it radiates light waves itself. In such instruments (for example, in styloscopes) analysis is conducted by means of emission spectra. Hence, the substance being tested is placed under conditions simulating those in which it radiates when on a star or in the upper atmosphere of the Sun. These are not the only procedures of analysis. Other methods used are fluorometry, radioautography (X-ray photography),

study of the isotope composition and distribution of mass of isotopes, magnetic investigations, etc. The analysis of soil samples provided by spacecraft requires the development of special techniques that exclude the possibility of contamination of the samples by substances of Earth origin. The analysis of the composition of gases contained in materials of extraterrestrial origin is performed in vacuum or in the atmosphere of an inert gas. Figure 6 shows up-to-date apparatus for analyzing soil samples delivered from the Moon by Soviet automatic interplanetary stations. The apparatus was designed and set up by Yu. Surkov, A. Kheifets, E. Rudnitsky, K. Danilov, and V. Glotov.¹

¹ See *Izuchenie vnezemnogo veshchestva v srede inertnogo gaza i sverkhvysokom vakuumе* (Analysis of Extraterrestrial Matter in the Medium of an Inert Gas and Ultra-High Vacuum), "Nauka" Publishers, Moscow, 1971.

Chemical Composition of Celestial Bodies. The Solar System

1. METEORITES

Iron is the principal component of a large number of meteorites (iron meteorites). Iron-stony meteorites (siderolites) and stony meteorites (chondrites and achondrites) also occur often.

Iron meteorites, in addition to iron, are usually composed of nickel, cobalt and other metals. These meteorites contain, on the average, 90 per cent iron, 8.5 per cent nickel, 0.6 per cent cobalt and approximately 0.01 per cent silicon. Alloys of iron and nickel are known as *kamacite* (the ratio of nickel to iron is 0.06) or *taenite* (the ratio of nickel to iron is from 0.14 to 1.0). Their combination is called *plessite*. Metals form crystal structures (Fig. 7). After polishing and pickling, the characteristic intersections of kamacite "beams" can be seen; they are noticeable because of the difference in the ability of kamacite and taenite to reflect light (Widmanstätten structure). Figure 8 shows the photograph of an iron meteorite. This meteorite fell in 1916 in the neighbourhood of Nikolsk-Ussuriysk and was described by O. Baklund in 1916. The magnetic properties of this meteorite were studied by N. Akulov and N. Bryukhatov. The meteorite contains 5.2 per cent nickel, 0.5 per cent cobalt, the remainder is iron. Although the isotope composition of a great number of meteorites is similar to that of



Fig. 7. Cross section of iron meteorite "Routon" (the Widmanstätten structure is visible)

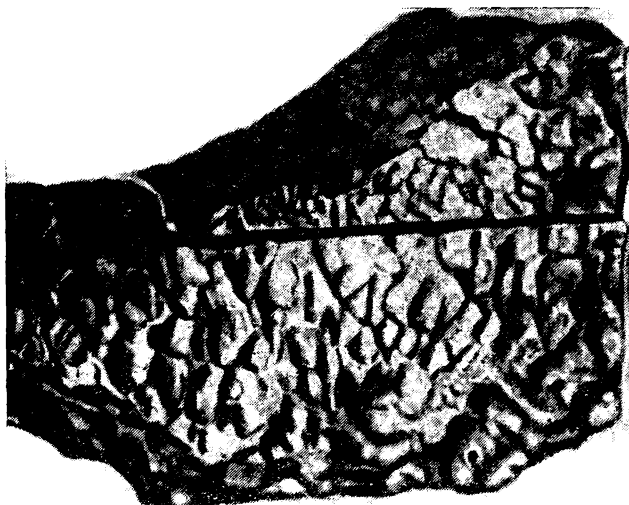


Fig. 8. Iron meteorite "Boguslavka" that fell on the Earth in 1916 and on falling split apart into two parts

rocks of Earth origin, the chemical analysis of meteorites has made it possible to discover in them interesting witnesses of the "life" of these celestial wanderers. It was found that the following isotopes occurred in them: ^{26}Al , ^{36}Cl , ^{44}Ti and others which are formed under the influence of cosmic radiation. Therefore the intensity of cosmic radiation and its duration can be determined on analyzing the isotopes.

The age of meteorites is found from the ratio of the quantity of radioactive isotope to the quantity of stable isotope. In investigations of iron meteorites it was actually the content of radioactive argon (^{39}Ar) and the stable isotope (^{38}Ar) that was determined. The radioactive isotope is produced by the action of cosmic rays on the nuclei of atoms in the meteorite, while the stable isotope accumulates in the course of time as a product of the decay of the radioactive isotope: the greater the content of the radioactive isotope, the younger the meteorite. In this way the age of certain meteorites was established; it turned out to lie in the range of 4 to 50 million years.

About 90 per cent of the meteorites that have fallen to the Earth belong to the class of chondrites. Chondrites have a very peculiar structure: they consist of small particles resembling congealed drops of silicates; these drops are called chondrules. The drop-like particles are cemented by the same substance from which they were formed (Fig. 9). Chondrites consist, in the main, of silicates and a small amount of iron, nickel, ferrous sulphide. According to A. Vinogradov the composition of chondrites includes olivine (44.53 per cent), pyroxene (26.87 per cent), feldspar (11.7 per cent), iron and nickel (together 9.0 per cent) and ferrous sulphide (6.97 per cent). The minerals olivine, pyroxene, feldspar occur on the Earth as well. The chemical composition of olivine is $(\text{MgFe})_2\text{SiO}_4$; of pyroxene,

$\text{Me}_1\text{Me}_2(\text{Si}_2\text{O}_6)$ where $\text{Me}_1 = \text{Ca}, \text{Na}, \text{K}$; $\text{Me}_2 = \text{Mg}, \text{Fe}, \text{Al}, \text{Ti}$. Feldspar consists of aluminosilicates.

The mineralogical composition and structure of chondrites give grounds for assuming that these minerals were formed at a temperature not exceeding



Fig. 9. Chondrites after removal of cementing rock (from a paper by A. Vinogradov)

1000°C. Then, apparently, they slowly (in the course of 10^8 years) cooled down to 300°C. Fusion probably occurred at a high pressure and then the volatile substances were lost and rapid crystallization took place.

Achondrites do not differ much from chondrites in their composition but they do not contain congealed drops, chondrules. Some of the achondrites are very similar to the Earth rock basalt. The abundance of individual elements in meteorites is given in Table 1.

Table 1

**Abundance of Certain Elements in Meteorites
(According to B. Levin and S. Kozlovskaya)**

Atomic number	Element	Number (per 10 ⁶ silicon atoms)	Atomic number	Element	Number (per 10 ⁶ silicon atoms)
3	Lithium	45	17	Chlorine	3,500
4	Beryllium	0.5	19	Potassium	3,000
5	Boron	6	20	Calcium	63,000
6	Carbon	6,000	26	Iron	723,000
7	Nitrogen	10	27	Cobalt	2,400
8	Oxygen	3,410,000	28	Nickel	38,000
9	Fluorine	200	30	Zinc	50
11	Sodium	40,000	31	Gallium	10
12	Magnesium	900,000	37	Rubidium	7
13	Aluminium	82,000	38	Strontium	18
			40	Zirconium	50
14	Silicon	1,000,000	41	Niobium	1
15	Phosphorus	8,000	44	Ruthenium	1.6
16	Sulphur	100,000	45	Rhodium	0.6

In the first place it should be noted that meteorites contain relatively large quantities of elements with even atomic numbers, and secondly, that elements with small atomic mass predominate in them. The first fact is associated with the particular properties of atomic nuclei having an even charge; the second, with the conditions under which the elements are formed in celestial bodies (see below).

Of special interest are carbonaceous chondrites which contain 20 per cent water and up to 5 per cent carbon. Compounds of carbon combined with hydrogen, nitro-

gen, sulphur and other elements have also been found in them.

Apparently, carbonaceous chondrites were never exposed to the action of high temperatures. They perhaps correspond most closely in their composition to that of the original cosmic dust cloud from which it is supposed the formation of planets began.

Carbonaceous chondrites contain organic compounds and are a rather rare type of meteorites. There are several varieties of carbonaceous chondrites (about 30). In them have been found hydrocarbons (aliphatic, cycloaliphatic, aromatic), carboxyl acids, complex high-molecular compounds having a system of condensed nuclei in their molecules, stable free radicals, etc. (Fig. 10). Carbonaceous chondrites also contain sulphur, carbonates, water of constitution¹; the content of deuterium (heavy hydrogen) in the organic compounds of chondrites is greater than in "Earth" substances².

Organic matter in carbonaceous chondrites is contained in a quantity of 30-50 mg per 1 g of matter; not all substances can be extracted by organic solvents. The following substances are usually used as solvents: water; methyl, ethyl, butyl alcohols; a mixture of benzene and ethyl alcohol; chloroform; petroleum ether; tetrachloromethane; benzene. The extract from meteorites of different types contains from 24 to 48 per cent carbon, 5-8 per cent hydrogen, 2-4 per cent nitrogen, 2-8 per cent sulphur, 1-5 per cent halogens (probably, chlorine) and 38-48 per cent oxygen (the remainder).

¹ Water of constitution is chemically combined water contained in compounds but not present as free molecules in them.

² It should be noted that other types of chondrites (enstatite chondrites) may contain organic matter which can be extracted by certain solvents.

By means of chromatography, fluoro-capillary analysis, infrared spectroscopy, ultraviolet spectroscopy

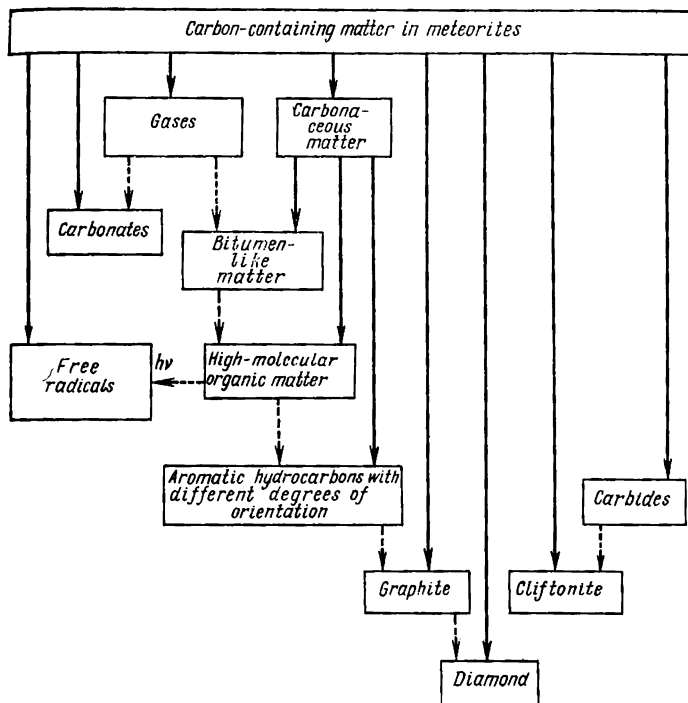


Fig. 10. Carbon-containing matter in meteorites (according to G. Vdovikin). Composition is shown by solid lines in boldface; the probable interrelationship between different forms of carbon, by dotted lines

and other methods, many of the constituents of the mixture of organic compounds have been determined. Carbonaceous chondrites also contain gases. The gases

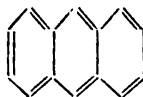
were analyzed by mass spectroscopy. In the gaseous phase of three carbonaceous chondrites M. Shtudier, R. Khayats and E. Anders have found hydrogen, helium, methane, water, carbon monoxide CO, nitrogen, nitric oxide NO, argon-40, carbon dioxide CO₂, butane, carbon oxysulphide, sulphur dioxide SO₂, carbon disulphide, krypton, xenon, toluene, and even naphthalene; ethyl and propylene benzene, dichlorobenzene, anthracene and phenanthrene. An astonishing variety indeed! How could all these compounds be formed? From where were they brought to us by such a small piece of mysterious carbonaceous chondrite? What part in the formation of these molecules was played by the radiation that spreads throughout space? Every question is a problem. Here are inert gases and together with them the active molecules of carbon oxysulphide COS, nitric oxide NO, sulphur dioxide SO₂, etc.; the aromatic hydrocarbons, condensed cyclic or ring compounds: benzene, naphthalene, anthracene:



Benzene



Naphthalene



Anthracene

How could their complex rings be formed? Under what conditions were the initial substances? Aromatic hydrocarbons predominate while for some reason or other there is no ethane present; the absence of ammonia is especially amazing. Evidently our knowledge of the chemical conditions in space is not sufficient as yet.

In order to ascertain the part played by radiation in the decomposition of hydrocarbons, special experiments were carried out with bituminous oil shale. The shale was exposed to a dose of radiation of from

300 to 3000 mrad¹. Under ordinary conditions of radiolysis (radiolytic decomposition) of complex organic compounds, methane and ethane are always produced. Ethane and methane were actually obtained in model experiments; there is neither ethane nor propane in meteorites, consequently radiolysis did not play an important role in the change of the state of organic matter of carbonaceous chondrites.

It is to be regretted that the results of analyses of extracts conducted by different authors do not agree very well; and the compositions of like fractions obtained from various specimens of carbonaceous chondrites also differ from each other.

Among the saturated hydrocarbons found were paraffin (about 17 per cent) and cycloalkanes (in varying quantities). The largest per cent falls on cycloalkanes with one ring (from 17 to 28 per cent); the smallest, on polycyclic molecules consisting of 5-6 rings (from 6.4 to 11 per cent). Alkanes occur in quantities from one to tens of micrograms per 1 g of matter ($\mu\text{g/g}$); these hydrocarbons contain from 15 to 23 carbon atoms. Carbonaceous chondrites also contain oxygenous organic compounds.

Very small quantities of the following substances have been found: alcohols, phenolic compounds and fatty acids. Saccharoses ($23 \mu\text{g/g}$); glucose, mannose and arabenose were found in an alcohol extract of carbonaceous chondrites. There are also sulphur-containing compounds; their analysis however is difficult because sulphur in meteorites is present in the free state in appreciable quantities and can react with the hydrocarbons in the process of the analysis. Chlorine is contained both as ionic compounds and as

¹ Mrad is the unit of radiation dose which is absorbed, equal to 10 ergs per gram of the medium.

chlorine derivatives of the aromatic hydrocarbons—chlorobenzene and dichlorobenzene.

One of the most acute and important questions arising in the chemical investigations of carbonaceous chondrites is, of course, the question of the possible biological origin of the compounds carried by these queer meteorites.

It cannot be said with certainty that a particular chemical composition indicates biological or non-biological origin of a substance. The compounds found in cells can originate outside of living systems as well.

It is true that amino acids, the constituents of proteins, can suggest the biological origin of a substance, but that is all. It has been proved that amino acids are produced, for example, during electric discharges in mixtures of methane and hydrogen, water, ammonia. Amino acids, apparently, are contained in carbonaceous chondrites — most likely glycine and phenylalanine.

The question whether other amino acids are present is not satisfactorily answered as yet. The accuracy of up-to-date analysis (chromatographic) is so high that traces of amino acids that get into the substance under test from the fingers of the analyst can be detected; therefore the presence of certain amino acids in the extracts of meteorites was compared with their presence in the fingerprints of the analyst and it was found that the occurrence of amino acids in the fingerprints almost coincided with that ascribed to the meteorite substance, i.e., the amino acids detected were simply impurities introduced by the analyst himself. The same thing happened in the case of chloronaphthalene which was believed to have been brought from outer space, but which actually got into the substance being tested from the polish used for parquet floors in the laboratory.

If purely chemical analysis cannot elucidate the origin of organic matter in chondrites, then perhaps physico-chemical methods can be of assistance. As a matter of fact, certain substances in living organisms possess a property on the basis of which the origin of the substance can be properly inferred. This property is known as optical activity.

The electromagnetic oscillations of a light wave occur in an ordinary ray of light in different planes. If the ray of light is passed through a crystal of the mineral Iceland spar, a wave can be isolated in which oscillations will occur in one plane. Such light is said to be plane-polarized. The polarized ray of light in passing, for instance, through water does not change the plane of polarization; but if sugar is added to the water, the plane of polarization of the ray after it has passed through this solution will be rotated through a certain angle. Substances that rotate the plane of polarization are called optically active substances. The rotation of the plane of polarization depends on the arrangement of atoms around a definite asymmetrical atom of the molecule. During a reaction the chances that laevorotary or dextrorotary substances (those that rotate the plane of polarization to the left or to the right, respectively) will be obtained are equal because the arrangements of atoms corresponding to rotation in one or the other direction are related to each other as an object to its mirror image. Hence, if the reaction is carried out in a test tube or flask, there is always obtained a mixture of compounds rotating the plane of polarization in opposite directions, i.e., a racemic mixture (that is optically inactive). But if the compound was formed in a cell, it can be optically active because for the cell it is not all the same how the atoms are arranged around the centre of the molecule.

That is why on detecting optically active compounds in any material, the investigator would have grounds for assuming the biological origin of the material. Obviously, proof of the presence in meteorites of substances that rotate the plane of polarization would indicate the biological origin of part of the organic compounds brought to the Earth from outer space. This would be evidence of the existence of some forms of life in celestial bodies. Slight rotation of the plane of polarization was actually observed by a group of scientists working in Nad's laboratory, but Khayats doubted their results which are being discussed to this day. Thus, the most interesting problem of space chemistry is still awaiting its solution. Let us briefly summarize what we have already learnt about meteorites.

The investigation of meteorites has yielded much valuable information. It has been ascertained that the composition of meteorites does not differ essentially from that of terrestrial matter. Assumptions have been made that meteorite matter is the parent matter from which the planets of the solar system were formed. Even the age of a meteorite and the duration of its travel in space can be surmised from the isotope composition. The presence of organic compounds in carbonaceous chondrites indicates important processes occurring at relatively low temperatures and raises the vital problem of the possibility of the biological origin of complex organic molecules. The scope of our knowledge of outer space is ever broadening and the continuation of investigations promises the discovery of new physico-chemical processes. At the present time the process of formation of diamonds in meteorites is attracting much attention.

Do diamond meteorites exist in nature? Can the appearance in the sky of a multi-ton sparkling crystal

or diamond shower be expected? Among the works of Jules Verne, the talented French novelist, is the witty fantastic novel "The Golden Meteor". It is about an inventor who devised the means of regulating the motion of meteorites and directed to the Earth an enormous meteorite that consisted solely of gold. When he understood, at the last moment, that this mass of gold would inevitably become the cause of conflicts and war between nations and would only bring suffering to the people, the inventor dropped the burning hot meteorite into the ocean. There are no golden meteorites and none are expected; neither are there any diamond mountains in outer space, but diamonds are found in meteorites and, what is of special importance, they are formed in them by collisions. The occurrence of diamonds in meteorites is quite rare and only a few diamond-containing meteorites are known.

The first information about such meteorites was obtained in 1886. In the former Penzenskaya province near the village of Novy Urey a stony meteorite fell down with a crash and a flash; according to all available data it broke up into three pieces. This event was described in great detail by P. Baryshnikov, a teacher, who sent the piece of the meteorite that he had found to St. Petersburg for investigation. The second piece sank into a swamp, while the fate of the third piece was altogether incredible—it was eaten up! The villager who found in his field a black stone that obviously fell from the sky, accompanied by startling light and sound phenomena, concluded that the stone would possess miraculous power and could favourably influence the course of an illness. The stone was broken up into small pieces and sold; the "medicinal" pieces were ground to a powder, then swallowed with water. But such medical treatment, naturally, brought neither benefit nor harm.

The piece that was sent to St. Petersburg was luckier — it fell into the hands of Professor P. Lachinov, the chemist and Associate Professor M. Erofeev, the mineralogist, and underwent careful analysis. It was found that the meteoric matter contained small grains



Fig. 11. Stony meteorite "Novy Urey" (photo from a paper by G. Vdovykin)

of diamond (of the carbonado type); according to rough calculation the weight of the meteorite amounted to about 2 kg and that of diamond constituted approximately 17.62 g. This meteorite went down in the history of science under the name of the "Novy Urey" meteorite and the scientists were awarded the Lomonosov Prize by the Academy of Sciences. Subsequently this type of meteorite came to be called ureylites; only five ureylites are known and they are carefully kept in museums in Leningrad, London, Calcutta and Kalgoorlie (in Australia).

The huge iron meteorite that created the Canyon Diablo also contains diamond inclusions. Figures 11, 12, 13 show the photographs of the meteorite "Novy

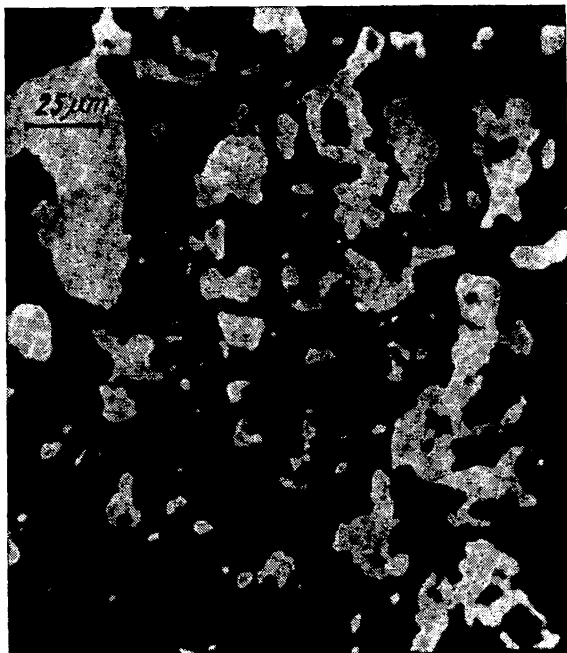


Fig. 12. Diamond particles from meteorite "Novy Urey" (photo from a paper by G. Vdovykin)

Urey", diamond particles isolated from it by the well-known investigator G. Vdovykin and a large diamond particle in the meteorite from the Arizona crater, respectively. Perhaps, of the greatest interest and value are not diamonds themselves (there are so few

of them and they are of low quality) but rather the knowledge of the conditions under which they were formed. The study of this question led to the conclusion that diamonds are produced in stony meteorites

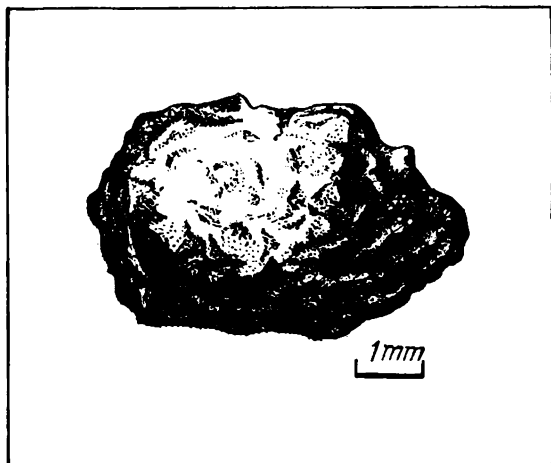


Fig. 13. Large diamond particle from "Canyon Diablo" meteorite (photo from a paper by G. Vdovkin)

as the result of the collision of asteroids. In the Arizona iron meteorite, diamonds were produced as the result of the impact of the meteorite against the Earth. At the very moment the terrific explosion and the terrible crash on the surface of the Earth took place, diamond crystals were formed from graphite inclusions. This may seem unlikely but direct experiments carried out in 1961 showed that at a temperature of about 800°C the instantaneous increase of pressure up to 600 thousand atmospheres gives rise to the formation of diamond from graphite in a millionth fraction

of a second! At the present time artificial diamonds are obtained in various ways and, of course, from the scientific and practical standpoint all these facts are very important. On the other hand, the fact that under certain conditions it has become possible to produce diamonds in the laboratory helps us to get an idea of the nature of the motion of asteroids and also of the process of the formation of diamonds in the crust of the Earth.

2. CHEMISTRY OF THE SOLAR SYSTEM

Spectroscopic analysis, the investigations of meteorites, astronomical and astrophysical data have made it possible to draw well-founded conclusions concerning the chemical composition of the parts of the universe nearest to us, i.e., of the solar system. The peculiar behaviour of substances of known composition under conditions existing in outer space also facilitates the solution of important problems associated with the evolution of celestial bodies, namely with the life of stars and galaxies. Thus, the methods and problems of chemistry are interwoven with the problems of cosmology, the branch of science that deals with the theories of the origin and evolution of the universe.

Our planetary system, according to the theory of O. Schmidt, originated from a cloud consisting of a mixture of cosmic gas and dust. There is no single point of view on the origin of the gas-dust cloud. O. Schmidt assumed that it originated as the result of interstellar matter being captured by the Sun. V. Fesenkov suggested that the cloud be formed together with the Sun. The further evolution of this cloud was associated with a process of gradual aggregation, i.e., growth of the mass of the particles.

There is hardly any loss of energy when molecules and atoms collide (elastic collision); when, however, a molecule and dust particle or two dust particles collide, a part of their kinetic energy is dissipated (i.e., is converted to heat and radiated as infrared rays.)

That is why the random motion within the cloud diminished while the rotary motion around the Sun was retained. A flat rotating disc was formed in which condensations of matter appeared. As the condensations increased in mass and were further condensed, the growing gravitational forces gradually attracted the surrounding matter to them to form the nuclei of planets. The orbital angular momentum of the particles from which the planet was formed must equal the sum of the orbital and rotary angular momentum of the planet.

In Shmidt's theory the partial dissipation of mechanical energy in the form of heat is also taken into account. This made it possible to understand certain features of the rotation of a planet (direct rotation). This theory showed the conformity with natural laws of the increase in radii of the orbits of planets and explained the difference in mass of planets of the Earth group and of far-distant planets (Fig. 14).

Possibly, five billion years ago in the cloud of gas and dust (i.e., a nebula) relatively slow motion of masses of matter occurred. The action of the magnetic field surrounding this nebula of stars decreased the total angular momentum, and this influence remained effective up to the time a certain density of matter of the nebula was achieved. Subsequently, condensation of the nebula took place without loss in angular momentum and resulted in the separation of an equatorial disc from the mass of the rotating matter. The formation of the disc and its magnetic interaction with

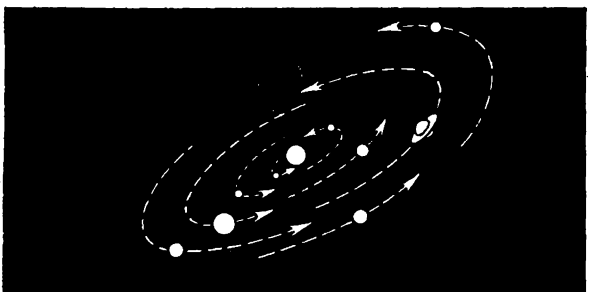
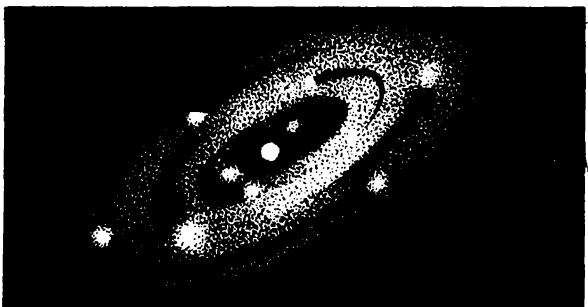
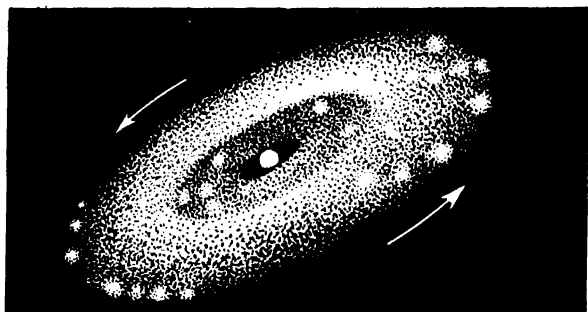


Fig. 14. Schematic drawing showing the formation of stars and planets from a cloud of gas and dust

the central part of the nebula would result, as shown by the astronomer F. Hoyle, in deceleration of rotation of the central part (i.e., the Sun) and subsequent withdrawal and breaking up of the disc. It is due to the breaking up and the condensation of aggregated matter that the planets were formed. All these processes could proceed in this way only in comparatively cool stars.

The temperature of the fragments into which the disc was broken up decreased rather rapidly and, accordingly, the possibility of the occurrence of particular reactions varied.

Meteorites, according to all data obtained, constitute the primary matter of the solar system, and their composition underwent relatively small changes from the moment they had been formed.

According to A. Vinogradov the material from which the planets of the solar system were formed was the same substances as those contained in chondrites, i.e., stony meteorites. It is clear, that if this is true, there are no grounds for expecting considerable diversity in the chemistry of the Earth, planets and meteoric matter. The elements everywhere in space are the very same ones and only specific conditions in different regions of the universe result in the different distribution of the elements and the preferred formation of particular molecules.

3. THE SUN AND PLANETS OF THE SOLAR SYSTEM

The chemical investigation of the Sun is carried out by spectroscopic analysis. In fact, the study of the spectrum of the central star of our planetary system turned out to be so fruitful that it has surpassed the achievements of analytical chemistry. The noble gas helium was first discovered on the Sun by spectroscopy.

pic analysis and only later was found on the Earth (*helios* is the Greek for Sun; *helium*, of the Sun). It should not be deemed, however, that it is easy to interpret the meaning of the innumerable electromagnetic oscillations that come from the Sun to the Earth and pass into spectrographs in observatories. A great number of interferences and complications must be eliminated by the spectroscopist observing the burning hot surface of the Sun, and sometimes the unusual conditions in which the spectrum is excited entirely distort the familiar picture and give rise to erroneous conclusions. Nevertheless, for more than a hundred years the spectrum of the Sun is under study, and at the present time the composition of the Sun, in the main, is known.

The immense mass of this star emits a continuous spectrum, just as any body would, that is heated to such a temperature at which the electrons become practically free, escaping from the atoms. The visible surface of the Sun is called the photosphere and is the source of the continuous spectrum; the gases on the surface are strongly ionized, ionization growing rapidly from the interior. That is why the gases almost immediately lose their transparency. As a result the photosphere seems to have a sharp boundary line although, as a matter of fact, the density of matter in it varies gradually.

The photosphere is not homogeneous: it has a discernible granular structure; bright flashes arise in it and dark spots appear. The sun spots possess magnetic properties and occur in pairs displaying opposite magnetism: one spot corresponds to the north pole, while the other one, to the south pole of a magnet bar.

The temperature of the photosphere (the mean temperature, since the photosphere consists of many layers) is equal to approximately 6000°C . Rays from the

photosphere penetrate the upper cooler layers of the Sun's atmosphere. The atoms and ions of various elements present in these layers absorb the spectral frequencies which they emit themselves. For example, sodium absorbs yellow rays (two characteristic yellow lines in the spectrum) which are emitted by glowing sodium vapours. On absorbing these rays (energy quanta), the excited sodium atom, of course, very soon emits them again, but the emitted quantum will not necessarily go in the same direction in which the initial quantum came; most probably, in this case, the quantum will have some other direction (a more or less random one). As a result of this, in the continuous spectrum of the photosphere there appear the dark lines observed by J. Fraunhofer, i.e. absorption spectra.

There is, however, a very faint light even in these dark (as compared to the general background) bands. Moreover it is possible, by shutting off the rest of the spectrum and successively projecting different parts of the solar disc where there are certain dark bands (characteristic of sodium, for instance), to obtain an idea of the distribution of a given element on the surface of the Sun and even to photograph the entire picture. The instrument for photographing the Sun in monochromatic light is called a spectroheliograph.

Above the photosphere there is a thin "reverse" layer (500 km thick). This name stems from the fact that during total solar eclipses, when the Moon covers the photosphere, instead of the dark lines in the spectrum bright lines emitted by this layer can be observed. Still higher lies the chromosphere which is slightly reddish in colour. This colour is one of the spectral lines of hydrogen. The chromosphere is about 6000 km thick and scattered in it are various atoms and ions, in particular a great number of calcium ions. About

400 lines belonging to different elements were observed in the chromosphere spectrum.

Still farther from the surface of the Sun is the solar corona, a very unstable and mobile part of the atmosphere of the Sun. It contains atoms, ions and electrons; there is evidence that iron ions are present in the corona, i.e., atoms that have lost part of their electrons (under these conditions iron atoms lose up to nine electrons). The lines of calcium, argon, nickel and other elements have been found in the spectrum of the corona. The temperature of the corona is very high and reaches millions of degrees (the reason for this is not known).

Hydrogen constitutes almost 75 per cent of the mass of the Sun; helium, about 24 per cent; all the other elements make up only 1-2 per cent. However, on an Earth scale, 1 per cent of the Sun's mass is not so little. The mass of the Sun is equal to 1.99×10^{33} g; consequently a hundredth part is 1.99×10^{31} g or 1.99×10^{25} tons! Even a millionth part of this enormous quantity is 3350 times greater than the mass of the Earth. The amounts of individual elements are determined by the relative intensity of the spectral lines, and sufficiently accurate data has been obtained for 60 elements; for elements whose atomic mass exceeds 57 the data is less accurate. The quantity of oxygen, carbon, nitrogen, sodium, iron and nickel on the Sun is rather large; that of lithium is small; boron and fluorine were found combined with hydrogen; radium, uranium, bismuth, rhenium are present in negligible amounts, while the artificial elements of the actinide series and unstable radioactive elements (promethium, astatine) as well as the halogens were not found at all.

According to the data of V. Cherdyntsev, the Sun's atmosphere contains the following amounts of ele-

ments per one atom of oxygen:

hydrogen	—560 atoms	aluminium	—0.0040 atom
carbon	—0.37 atom	silicon	—0.037 atom
nitrogen	—0.76 atom	sulphur	—0.016 atom
magnesium	—0.062 atom	potassium	—0.00029 atom
sodium	—0.0035 atom	calcium	—0.0031 atom

The presence of gold (the alchemists' symbol for which was the Sun) is doubted; in any case there is not very much of it on the Sun. Attention should be paid to the abundance of hydrogen and helium. This is very significant and will be discussed below.

Now let us turn our attention to the planets surrounding the Sun. It should be noted that in general the chemical analysis of planets is very difficult because planets only reflect sunlight and therefore their composition must be inferred from the spectrum of reflected light (reflection spectrum). Such spectra are difficult to interpret and often fail to give grounds for unambiguous conclusions. The data obtained concerning the composition of the atmosphere of planets is somewhat more reliable. If spectroscopic analysis is not always capable of giving information about all the molecules (sometimes rather complex) which can be formed in the atmosphere of the planets, theoretical calculation comes to its aid. At the first glance this may seem to be a hopeless task: how can the physicist, chemist and mathematician without investigating the atmosphere of a distant planet calculate its composition?

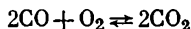
Actually, of course, they must know something about the planets, but the salient feature of their work, like that of the paleozoologist, is that from very meager initial data it leads to broad and important conclusions. From one bone found in a fossil of times long

past, the paleozoologist familiar with the laws of his science can construe a picture of the general appearance of an animal, and from the concentration of three, four or five elements the physico-chemist can predict just what compounds are formed. Of course, it is necessary to know the temperature, pressure and the properties of the initial and end products; but the physical characteristics are usually more or less known and the laws of chemistry, as has been ascertained, are the same everywhere in the universe.

The basic law of investigations is that under definite conditions, for instance, at a given temperature and pressure a reaction can proceed spontaneously only if it performs positive work. The work of a reaction is a relatively simple concept. It is known, for example, that in an operating storage battery a chemical reaction takes place between lead, its oxide and sulphuric acid. This reaction resulting in the formation of lead sulphate produces electrical energy. If, after discharge we desired to return the storage battery to its former state, i.e., to obtain the initial substances we would have to perform work, that is to recharge the battery by means of an external source. The storage battery discharges by itself although it must be charged. This means that the reaction proceeds spontaneously, performing useful positive work.

By applying thermodynamics it has become possible to prove that a relationship exists between the work of a reaction and the equilibrium constant of a reaction. From the general course in chemistry it is known that when equilibrium is attained in a chemical reaction, the rates of the direct and reverse processes become equal.

The equilibrium constant, for example, for the reaction



is the ratio at equilibrium of the concentrations of the molecules participating in the reaction:

$$K = \frac{[\text{CO}_2]^2}{[\text{O}_2][\text{CO}]^2}$$

The useful work of a reaction at a given temperature can be determined from the equilibrium constant and the concentrations of the initial and end products (reactant and reaction products, respectively).

The maximum useful work at different concentrations and temperatures can be calculated by means of thermodynamic equations. Thus, it is possible to foretell what reactions can take place and what reactions cannot occur under given conditions. Evidently, knowing approximately the conditions on the planets, stars or on our Earth in those ancient times it is possible to determine what reactions proceeded and what products were formed. In order that such calculations make any sense it is only necessary to be sure that equilibrium does exist in the celestial body under study. However, the question of equilibrium is not a simple one. Powerful radiation and rapid processes which are very likely to occur in outer space are apt to disturb chemical equilibrium and then thermodynamic calculations will be of no use.

At one time the majority of scientists working in the field of space chemistry and physics believed that there were no grounds for calculating reactions proceeding from the assumption of equilibrium. Thus, they rejected one of the most reliable means of investigating possible reactions. In recent years, however, a marked change in the attitude towards the problem of equilibrium has been manifested. More and more data and theoretical reasoning speak in favour of the possibility of the equilibrium state being attained in chemical processes on celestial bodies. If equilibrium can be

achieved, then the modelling and calculation of chemical systems is quite possible.

E. Lippinkot, R. Ekk, and K. Sagan gave their attention to the carbonaceous chondrites already spoken of above. As is known, a great number of organic compounds of all kinds are contained in carbonaceous chondrites. If all these compounds were formed under conditions close to those of equilibrium, an attempt can be made to calculate, from the properties of these compounds, what substances and in what proportions must have been formed in the mixture brought to the Earth by the carbonaceous chondrites. It was assumed that graphite did not take part in the reactions leading to equilibrium; graphite is not readily formed from organic compounds, and scientists did not take it into account in their calculations.

Calculations performed with the aid of computers have showed that proceeding from carbon, hydrogen, nitrogen, sulphur, oxygen and chlorine, carbonaceous chondrites would actually contain the very compounds that were found in them by chemical analysis and in about the same proportions.

The success of these calculations prompted the authors to attempt the calculation of the atmosphere of planets. E. Lippinkot, R. Ekk and K. Sagan assumed that equilibrium is reached in the lower layers of the atmosphere into which ultraviolet radiation fails to penetrate. In order to appraise the accuracy that could be attained in the calculation of the composition of the atmosphere of planets, the investigators calculated the composition of the Earth's atmosphere and compared the results of calculation with experimental data. A study was carried out of the balance of compounds for all combinations of carbon, nitrogen, hydrogen and oxygen.

An extract from the tabulated data obtained by them is given below. The experiments corresponded to a pressure of 1 atm and a temperature of 280°K. The only equilibrium state corresponded to the composition of the Earth's atmosphere:

nitrogen	—0.78 parts by volume (by calculation)
oxygen	—0.21 parts by volume (by calculation)
argon	—0.01 parts by volume (by calculation)
water vapours	—0.001 parts by volume (by calculation)
carbon dioxide	— 3.3×10^{-4} parts by volume (by calculation)

This convincing result gives grounds for believing that calculations of the composition of the atmospheres of other planets carried out by these scientists are also close to the truth.

Such calculations should proceed from the given concentrations of substances in the atmosphere, and then the concentrations which correspond to an equilibrium state should be calculated. Thus, in the example of the Earth's atmosphere the parts by volume of the gases (0.780 for nitrogen, 0.209 for oxygen, etc.) taken initially are those actually found in the atmosphere. To calculate the atmospheres of other planets it is also necessary to begin with experimental data. Lately, highly valuable information concerning the composition of the atmospheres has been provided by Soviet interplanetary stations. The value of the results of calculation, of course, depends on the reliability of the initial assumptions.

Thus calculations of the composition of the atmosphere of Venus were first based on the arbitrary assumption that nitrogen predominates in it. Later when precise data on the composition of the atmosphere of Venus was provided by the Soviet stations *Venera-4* and *Venera-5*, it turned out that this assumption was false and that the main constituent of Venus's atmosphere was not nitrogen but carbon dioxide. Consequently,

the former conclusions were no longer valid. If, however, the initial suppositions are sufficiently grounded, the equilibrium method can attain valuable results. As concerns the atmosphere of Mars, the assumption of equilibrium and the initial data available are, apparently, reliable. Calculations lead to the conclusion that at a temperature of 240°K and a pressure of 0.05 atm the atmosphere of Mars contains from 0.82 to 0.90 parts by volume of nitrogen, approximately 0.1 of oxygen, the same amount of carbon dioxide and about 10^{-5} of water vapours. The quantities of other compounds (in particular, oxides of nitrogen) are negligible.

When studying the composition of the atmosphere of Jupiter it was supposed that below the cloudy zone the parts by volume of water are comparable with the parts by volume of methane and ammonia, the presence of which on this planet is beyond doubt. Calculations were made for a pressure of 1 and 1000 atm and a temperature of 200 and 350°K , and the results obtained were of great interest (see below).

The temperature of the upper layers of the atmosphere of a planet can be approximately measured with the aid of a thermocouple placed in the focus of a telescope. The heat radiated by the planet falls on one of the junctions of the thermocouple while the other junction has a constant temperature. Under these conditions there arises a temperature difference which produces in the thermocouple a thermoelectric current by which the intensity of heat radiation is measured.

4. THE PLANETS

Prior to the development of spectroscopic analysis of reflected light and other refined methods for determining the composition of the planets of the solar

system it was supposed by some scientists that they are all alike in composition. This is not so. Even the comparison of the density of the matter of planets shows that their composition cannot be the same. Planets are clearly divided into two groups.

The planets nearest to the Sun (the inner planets) have a density of from 5.62 to 3.35. The outer planets, Jupiter, Saturn, Uranus, Neptune, have a smaller density: from 0.71 to 2.43 (see Table 2).

Table 2

Density of Planets	
Planet	Density
Mercury	5.62
Venus	5.15
Earth	5.517
Mars	4.00
Moon	3.35
Chondrite asteroids	3.5 (approximately)
Jupiter	1.35
Saturn	0.71
Uranus	1.60
Neptune	2.43
Pluto	?

Mercury, Venus, the Earth, Mars, the Moon are undoubtedly solid bodies. They consist of silicates, aluminosilicates, carbonates and other minerals constituting their surface crust. There is a core containing the heavier elements with a large atomic mass in these planets.

The giant planets, Jupiter, Saturn, Uranus, Neptune, consist of less dense materials: mainly hydrogen,

helium, methane, ammonia and other gases. There is insufficient evidence of the existence of a solid core in these immense gaseous or semiliquid masses.

Mercury contains a ferromagnetic core¹ and has an intense magnetic field. It is supposed that it is surrounded by powerful radiation belts; then its atmosphere should be ionized to a high degree. One side of Mercury is always turned to the Sun; the other side is always in the dark. In order to measure the temperature of Mercury Nicholson and Pettit placed a thermocouple in the focus of a telescope of a 2.5-m diameter and measured the current appearing in the thermocouple due to the infrared radiation of the planet. It was found that the temperature of Mercury varies in a very wide range, from -70 to $+437^{\circ}\text{C}$. The low temperature could have been even lower. The relatively small frost on Mercury can probably be explained by the influx of heat; possibly heat gets into the cold zones due to corpuscular solar radiation deflected by the magnetic field of the planet. For a long time the very existence of an atmosphere on Mercury was questioned. Apparently, the pressure of the atmosphere, consisting mainly of nitrogen (90 per cent) and carbon dioxide (10 per cent), lies in the range of 1 to 20 mm Hg.

Venus and Mars, like the Earth, have an iron core surrounded by a mineral (principally silicate) layer. On Venus there is a large amount of carbonates, the thermal decomposition of which resulted in the accumulation of carbon dioxide in the atmosphere of this planet.

According to the data provided by the Soviet interplanetary stations *Venera-4*, *Venera-5*, *Venera-6* and *Venera-7* the atmosphere of Venus consists of

¹ According to the data of S. Kozlovskaya, the total content of metallic iron in Mercury (in the core of the planet and in the mantle) constitutes approximately 58 per cent.

97 per cent of carbon dioxide and contains not more than 2 per cent nitrogen, about 1 per cent water vapours and not more than 0.1 per cent oxygen. The temperature on the surface of the planet is about 500°C; the pressure, approximately 100 atm.

Before all this data became known, it was supposed that Venus resembled the Earth and that there might be life on it. Many fantastic novels were written that dealt with the forms of life on Venus. Large beasts (like the extinct dinosaur of the Mesozoic Era on the Earth) were supposed to live in stifling hot swamps on this planet enveloped in clouds. Actually, the conditions on Venus exclude the possibility of the development of life because the temperature on the surface is too high. The majority of organic compounds decompose at 500°C.

The next planet, which is farther from the Sun, does not resemble the others. It is enveloped by an atmosphere and seems to be bluish in colour. If travelers from far-distant galaxies were to pay a visit to the solar system, they would probably find this planet to be the most interesting one; there must surely be life on it. This is our Earth! According to all available data life on the planets could occur only on the Earth and Mars.

The scorched crust of Mercury, the burning hot valleys and cliffs of Venus immersed in twilight because of the dense clouds, the cold Moon and the ammonia-methane masses of the giant planets are unsuitable for supporting life, at least its higher forms. Therefore the inhabitants of the Earth, with all due modesty, have good reason to be proud of their homeland and its remarkably diversified nature. What does the Earth consist of? What is its chemistry? If it was not very easy to answer such questions when discussing the composition of planets, in this case difficulties of

another kind arise. The material available to the science that studies Earth chemistry, geochemistry is so great that in the scope of this book it is impossible to set down even the most fundamental facts known. Nevertheless, we immediately answer the question concerning what elements dominate in the composition of the Earth; they are oxygen and silicon. These two elements are found in so many atoms that they stand out sharply against the others. However, we should not jump to conclusions in a hurry. The Earth is not homogeneous. Geochemists divide it into geospheres: the atmosphere, the hydrosphere (consisting of water) and the lithosphere, i.e., the solid part.

The atmosphere consists, as is known, of nitrogen (78.08 per cent by volume) and oxygen (20.94 per cent). Not everyone knows that more or less constant constituents of the atmosphere are: argon (0.934 per cent by volume; other inert gases constitute only thousandth and tenthousandth parts of a per cent), mercury (0.02 gamma/m^3)¹, iodine (1 gamma/m^3 and on seashores up to 52 gamma/m^3) and radon in a still smaller amount. This data pertains to the lower part of the atmosphere, the troposphere. Besides, in the atmosphere there are water vapours, carbon dioxide, a very small amount of hydrogen and accidental impurities.

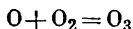
It is believed that the primary atmosphere of the Earth disappeared. The secondary atmosphere, containing less inert gases, appeared as the result of degasification of the interior of the Earth. The primary atmosphere contained a relatively large amount of hydrogen. The pressure of hydrogen according to S. Miller and Kh. Yury, 4.5 billion years ago, was equal to $1.5 \times$

¹ Gamma is a unit for measuring the quantity of a substance; it is equal to one millionth part of a gramm (Tr.)

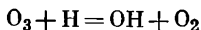
$\times 10^{-3}$ atm. Assuming equilibrium, the investigators concluded that the pressure of methane in those times long past could be very great and nitrogen, probably, was present in the form of ammonia. Hydrogen, ammonia, nitrogen, methane, and probably the oxides of carbon were the chief constituents of the primary reducing atmosphere of the Earth.

Whereas the lower layers of the atmosphere in our times have a constant composition and are in a state close to that of equilibrium, in the higher layers equilibrium is disturbed by radiation. The upper regions of the Earth's atmosphere already border on outer space. The boundary line that separates these regions from space is not a distinct one; the density of the gases diminishes gradually. There is a gradual increase in the role of solar cosmic radiation in the chemical reactions characteristic of the upper layers of the atmosphere. There is even a special term "chemosphere" for regions where under the influence of solar radiation the processes occur with the participation of ions and elementary particles. The chemosphere lies approximately at a height of 100 km; the pressure there is only 0.001 mm Hg.

At high altitudes, ultraviolet radiation ionizes almost all the gas molecules. Oxygen in the chemosphere is mainly in the nascent, i.e., in the atomic state. The collisions of oxygen atoms result in the formation of O_2 molecules, and the interaction of oxygen atoms and O_2 molecules produces ozone:



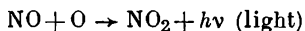
The ozone produced partially reacts with hydrogen to form the OH radical:



The production of ozone plays an important part in Earth chemistry. The fact is that ozone readily

absorbs ultraviolet rays and, protecting the surface of the Earth from most of this radiation, it inhibits photochemical reactions that destroy organic compounds. It is supposed that this effect created favourable conditions for the development of photosynthesis. Photosynthesis, i.e., the process of formation of carbohydrates from carbon dioxide and water, catalyzed by chlorophyll, not only promoted the development of microorganisms and plants but increased the concentration of oxygen in the Earth's atmosphere. The oxygen that we breathe appeared approximately 0.3 billion years ago as the result of photosynthesis in living cells and, partly, of photodissociation of water molecules in the atmosphere.

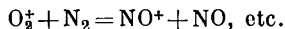
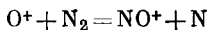
Investigation of the upper layers of the atmosphere is conducted with the aid of special rockets. One of these rockets ejected a cloud of nitric oxide, NO, at a height of 100 km. As a result of this, a bright light appeared caused by the reaction between oxygen atoms and nitric oxide molecules. This compound, as is known, readily reacts with oxygen molecules, O₂, in air. The reaction of nitric oxide and oxygen atoms in the upper layers of the atmosphere proceeded with greater intensity and was accompanied by the radiation of a light quantum:



Investigation of this phenomenon made it possible to calculate the lower boundary of the atmosphere, above which the oxygen molecules are, for the most part, dissociated into atoms. This boundary is at a height of about 95 km.

The Sun's radiation also causes dissociation of nitrogen molecules. These stable molecules dissociate in the upper part of the atmosphere into nitrogen atoms though to a much less degree than oxygen mole-

cules (the number of nitrogen atoms produced is equal to 1 per cent of the number of oxygen atoms). Nitrogen and oxygen react in the atomic state to form oxides of nitrogen, NO and NO₂. Many molecules resulting from processes occurring in the chemosphere carry surplus positive or negative charges, i.e., they are molecular ions. N⁺, N₂⁻, O₂⁻, NO₂⁻, NO⁺, O⁺ and other ions are formed. Particles can react with each other so that the charge is transferred from one to another, for instance:



In the daytime ionization in the atmosphere is more intense; at night the number of ions diminishes. The processes, in which ions are produced due to the action of radiation or disappear or change due to various reactions, always occur in the atmosphere.

Still greater chemical action is exerted by the flow of such particles as protons and electrons. Only neutrons are an exception; they penetrate into celestial bodies and space almost without any signs of interaction with molecules or atoms.

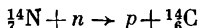
Already in 1912 it became known that particles burst into the Earth's atmosphere with an enormous release of energy (sometimes reaching billions of electron volts), and many of them penetrate to the surface of the planet. Every minute one particle falls, on an average, on each square centimetre of the Earth's surface. Later, it was proved that the particles observed on the surface of the Earth are frequently secondary particles, i.e., they are produced as the result of the interaction of primary radiation and atoms and molecules in the atmosphere. Primary radiation is made up, first of all, of protons moving at a great velocity; besides, in cosmic rays heavier particles were found;

the nuclei of helium, lithium, beryllium, boron, carbon, nitrogen, oxygen and other elements.

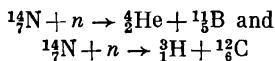
Up to now the origin of cosmic rays is a debatable question. The most probable assumption is that cosmic rays are produced as the result of thermonuclear reactions in supernovae, somewhere deep in the Galaxy; other reasons for the origin of this high-energy radiation in space are also possible.

The low density of interstellar matter is favourable for maintaining the ionic state: protons can wander in space for a long time without attaching electrons. The short-wave radiation of stars, for instance, the Sun, is also conducive to the formation of ions. E. G. Fermi proved that the interaction of a proton with the magnetic fields present in space must cause a gradual increase in the velocity of the proton. The proton on accumulating an extremely high energy of billions of billions of electron volts becomes an imposing missile and its collision with an atom can, of course, lead to a great variety of conversions. Thus, in the upper layers of the atmosphere there ensues a series of processes which result in the production of secondary particles such as neutrons, γ -quanta, and the unstable particles called mesons.

On an average, every second 2.6 neutrons are formed in 1 cm³ of the atmosphere. These neutrons constantly supply the Earth with the $^{14}_6\text{C}$ carbon isotope as the result of the reaction

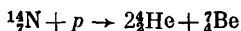


About 10 kg of $^{14}_6\text{C}$ are formed per year. Besides, the following reactions proceed:



the latter reaction produces tritium (an isotope of hydrogen).

Protons are even capable of converting nitrogen to beryllium (${}^7\text{Be}$):



This isotope of beryllium was found in rain water.

Even the composition of the surface layers of rocks changes slowly as a result of the constant bombardment of cosmic rays.

In the hydrosphere, besides water, large quantities of salts and organic compounds are found. This is very important because, apparently, life was generated on the banks of seas and oceans, where the borders of three geospheres converged.

The average composition of the hydrosphere, in per cent, is as follows: oxygen, 85.82; hydrogen, about 10.72; chlorine, 1.89; sodium, 10.6; magnesium, from 0.1 to 1; the content of all the other elements amounts to 0.22 per cent. Among these other elements are boron, fluorine, bromine, rubidium, lithium, iodine, phosphorus, zinc, iron, copper, arsenic, aluminium, lead, vanadium, manganese, selenium, nickel, tin, cobalt, molybdenum, titanium, germanium, scandium, mercury, silver, gold and even uranium and radium! The ocean is verily a storehouse, a chemical storehouse, the inexhaustible source of all kinds of compounds. It is to be regretted that most of the compounds are very scattered; their concentration consequently is very low and this, of course, makes it difficult to obtain them from the water.

The lithosphere is the outer solid rocky shell of the planet, known as the crust of the Earth. The crust consists of a thin sedimentary zone of a magnitude (thickness) of only about 1.5 km, a granite-gneiss zone up to 40 km thick and a basalt zone of a thickness of approximately 30 km, that passes into the mantle.

The crust was formed by the gradual melting out and, partly, degasification of substances in the mantle (according to A. Vinogradov). In this process a redistribution of substances took place: low-melting compounds and elements migrated to the top zones, while the high-melting substances concentrated in the bottom.

The most widespread elements in the Earth's core, as has been already noted, are oxygen and silicon. More than 49 per cent of the mass of the crust is that of oxygen and 26 per cent that of silicon. Aluminium occupies the third place—7.45 per cent of the mass; then comes iron, 4.20 per cent; calcium, 3.25 per cent; sodium, 2.40 per cent; potassium, 2.35 per cent; magnesium, 2.35 per cent, hydrogen, 1 per cent; the content of all the other elements is expressed by fractions of a per cent. Calculation according to the number of atoms (atom per cent) gives a somewhat different sequence of elements. There is an abundance of hydrogen atoms (see Table 3).

Table 3

The Most Widespread Elements in the Earth's Crust

Element	Content, atom per cent	Element	Content, atom per cent
Oxygen	53.39	Magnesium	1.72
Hydrogen	17.25	Calcium	1.41
Silicon	16.11	Iron	1.31
Aluminium	4.80	Potassium	1.05
Sodium	1.82	Carbon	0.51

The content of each of the rest of the elements is less than 0.5 per cent.

As can be seen, elements with low atomic masses and small atomic numbers (the number of the element

in Mendeleev's periodic system) predominate in the Earth's crust, and oxygen, hydrogen, silicon and aluminium constitute the base of the core (according to A. Fersman). However, lithium, beryllium, and boron are contained in very small quantities; these are the "scarce" elements.

Elements with even atomic numbers and even atomic masses are more dominant in the crust than those with odd atomic numbers and masses. This fact is important and, as we shall see below, is quite characteristic.

The relatively high temperature of the Earth undoubtedly favoured the development of all kinds of chemical reactions on its surface and especially in the waters of the hydrosphere.

The Earth probably was never a blazing fiery globe as was supposed for a very long time by astrophysicists. The temperature of the Earth in the long distant past could have been very high as compared to its temperature at the present time, but apparently, the temperature was never like that characteristic of the interior parts of the Sun, for instance. The reason for the heating of the globe was the decay of atoms of radioactive elements. Thirty five years ago V. Khlopin, an outstanding Soviet scientist, showed that the reserves of radioactive substances in the Earth's crust are sufficient to maintain the temperature of the Earth at the present level. It is now believed that the Earth is heated by the radioactive decay of the isotopes of uranium, thorium and potassium. The role of the heavy potassium isotope (^{40}K) perhaps was great in the prebiological period of the development of the Earth and is essential in our times as well.

The nonuniform distribution of this fuel is, of course, the reason why heating does not proceed uniformly, and this gives rise to hot spots and zones of

high pressure. The Earth has not, as yet, reached a state of thermal equilibrium or balanced geological structure. Earthquakes, volcanic and geyser eruptions indicate constant activity of powerful chemical and physical forces in the interior of the Earth.

In the early periods of the evolution of the Earth, when compounds with low melting points were melted out, gases were also liberated and gradually formed the Earth's atmosphere. The atmosphere thus produced contained a small amount of inert gases although they occur in relatively large quantities in the cosmic interstellar matter. A few of them (helium, neon) are the products of those nuclear reactions that are constantly taking place in the interior of stars.

Now let us discuss the nearest neighbour of the Earth, the Moon (Fig. 15). There is absolutely no atmosphere around the Moon. Its outer shell consists, apparently, of a solidified mass (the crust) under which there is the more solid mantle. Above the crust there is an outer layer (2 km) consisting of stones and rocks crushed and fused together due to the heat evolved by falling meteorites. The crust consists of basalt rocks (25 km); under this layer lies coarse-grained igneous rocks.

Chemical analysis of lunar soil samples provided by Soviet automatic stations *Luna* and the *Apollo* expeditions showed that the soil contains silicon dioxide, SiO_2 (40 per cent), aluminium oxide (11.2 per cent), and also compounds of the metals: magnesium, calcium, iron, titanium (in terms of the oxides 11.7, 10.7, 21.3, 37 per cent, respectively). The soil samples, however, brought to the Earth by *Luna-16* and *Luna-20* differed from each other. As might have been expected, the composition of rocks on the surface of the Moon in various zones is different. Mass-spectrometric analysis has made it possible to determine quantitatively

more than 70 elements that make up the composition of lunar soil (regolith).

The Soviet interplanetary station *Luna-16* took the soil sample from the part of the Moon called *Mare*

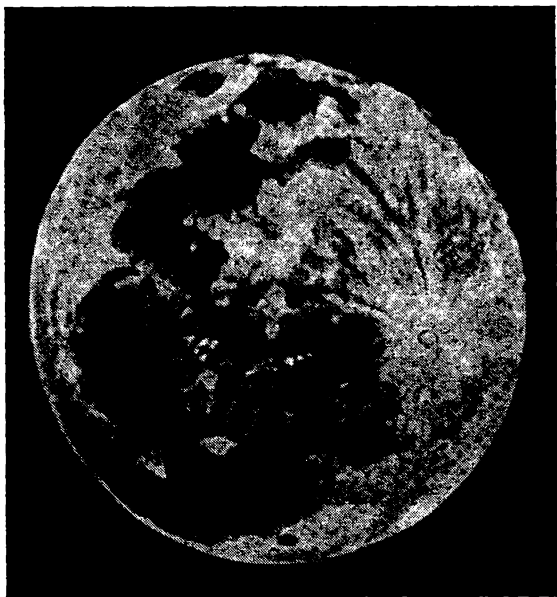


Fig. 15. Photograph of the Moon

Foecunditalis (Sea of Fertility). In this “sea” the soil is composed essentially of rocks close to basalt in composition. There is a large number of inclusions in it, which resemble fused glass—something like glass globules. *Luna-20* provided soil samples from the continental part; there were fewer glass inclusions in it. These samples were composed mainly of minerals

of the anorthosite type¹. The mineral anorthosite is found on the Earth; it belongs to the magmatic rocks of the group of plagioclase feldspars. Usually anorthosite consists of labradorite and inclusions of pyroxene. Labradorite is a mixture of albite, $\text{NaAlSi}_3\text{O}_8$, and anorthite, $\text{CaAl}_2\text{Si}_2\text{O}_8$; it is characterized by a beautiful play of colours (it is colourless or grey-white with tints of blue-green). Many widespread minerals (gabbro, basalt, diabase and porphyrite rocks) contain labradorite; under the influence of water it forms hydromica and kaolin.

Academician A. Vinogradov who supervised the analysis of the lunar soil observed that the solution of the problem of the formation of anorthosites on the Moon would help to understand the geological processes on the Earth where anorthosites were found in ancient rocks of an age of 3.5 billion years. Anorthosites are extruded on the surface during rapid eruption of magma at high temperatures. Thus, the Moon was probably once a molten planet.

Iron in the fine-grained and free state was also found in the lunar soil. It is of interest that this iron is practically not oxidized in air. Minerals containing iron were found, as well as those containing titanium and nickel.

Table 4 (according to data of A. Vinogradov) presents the latest data on the composition of the lunar soil taken from different regions of the Moon.

For comparison we'll give data on the composition of soil from *Mare Tranquillitatis* (Sea of Tranquility) provided by U.S. spacecraft; in this case crystalline

¹ With the aid of an X-ray spectrometer it has been proved that there is much more aluminium and silicon in the continental regions of the Moon than in its seas. The latter are covered with dark lava while the continental regions consist of rocks of a lighter colour—anorthosites.

Table 4

Composition of Lunar Soil

Component	Crystalline basalt rock (Luna-16)	Crystalline anorthosite with olivine (Luna-20)	Soil (regolith) (Luna-16)	Soil (regolith) (Luna-20)
Silicon dioxide	42.95	44.4	41.90	44.4
Aluminium oxide	13.88	19.1	15.33	22.9
Ferrous oxide	20.17	6.9	16.66	7.03
Calcium oxide	10.8	13.3	12.53	15.2
Magnesium oxide	6.05	13.37	8.78	9.70
Titanium dioxide	5.5	0.52	3.36	0.56
Sodium oxide	0.23	0.48	0.34	0.55
Potassium oxide	0.16	0.47	0.1	0.10

and porous rock samples and lunar dust were analysed¹ (see Table 5).

Uranium-236 and neptunium are also found in lunar rocks. The uranium isotope is contained in larger quantities than in Earth rocks (from 5 to 350 times more). The amount of neptunium per 1 g of lunar dust amounts to 25 million atoms. These elements were probably formed on the Moon by the action of powerful streams of high-energy protons liberated during solar flares.

The planet Mars, which has, perhaps, aroused the most fervent arguments concerning the conditions prevailing on its surface, has an atmosphere much more rarified than that of the Earth. The atmospheric pressure on Mars is only 0.08 of the Earth's atmospheric pressure. The main constituents of the atmosphere of this planet, according to all data available, are nitro-

¹ It has been supposed by some scientists that there is water in the permafrost layer or rocks on the Moon.

Table 5

Lunar Rocks from Mare Tranquillitatis

Sample	Oxides, per cent												
	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	Cr ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	H ₂ O
Crystalline rock	40.77	11.82	7.92	0	19.79	0.33	0.22	7.74	11.58	0.51	0.29	0.18	0
Porous rock	40.22	12.28	7.78	0	19.77	0.36	0.22	8.06	10.27	0.52	0.29	0.18	0
Lunar dust	42.25	7.24	13.53	0	15.80	0.27	0.20	7.97	11.96	0.43	0.13	0.14	0

gen and carbon dioxide. There is very little oxygen and water vapours on Mars, approximately a thousand times less than in the Earth's atmosphere. The conditions on Mars resemble somewhat the conditions in the high-mountain regions of our planet. In general, in view of the fact that the temperature in the summertime during the day is equal to approximately $+10^{\circ}\text{C}$ and in the wintertime and at night it is about -90°C , it can be assumed that some forms of Martian life, in particular vegetation, may exist. The spectra of light reflected from the surface of Mars, studied by the Soviet scientist Tikhov, resemble the reflection spectra from the surface of the Earth in the regions covered by forests; besides, the colour of certain parts of the surface of Mars changes with the season, as it should if the colour is due to reflection from vegetation.¹

It is quite possible that the chemical composition of the compounds forming the surface of Mars is similar to that of the Earth's surface and is one of the most complex compositions in abundance and variety of compounds.

The atmosphere and the temperature, radiation, and pressure typical of Mars were simulated in laboratories on the Earth. It was found that even under such drastic conditions life is in fact possible; unicellular organisms such as bacteria developed in model layout.

Mars was studied at a close distance by the Soviet automatic interplanetary station *Mars-1* launched from the Earth on November 1, 1962 in the direction of Mars, approaching it in 230 days. Various important scientific data was transmitted by radio communi-

¹ The study of the infrared spectrum of Mars, however, did not reveal in it any signs characteristic of the chlorophyll spectrum; that is why the existence of vegetation on Mars has not been proved.

cation 61 times. Later in 1964-1969 the American *Mariner* automatic interplanetary stations flew by the

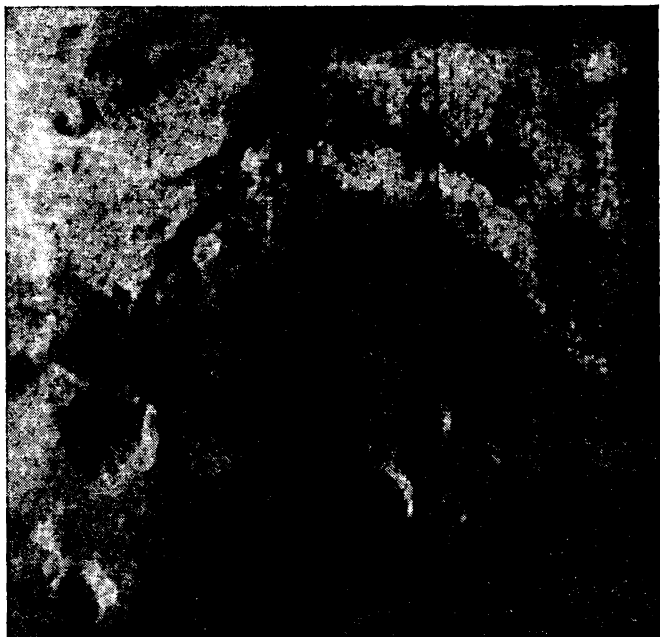


Fig. 16. Surface of Mars (photograph taken by *Mariner-4* at a distance of 12,000 km)

equatorial and polar regions of the planet and approached its surface at a distance of only about 3000 km from it. The photographs relayed to the Earth showed the mysterious red planet and the Moon bear a great resemblance to each other (Fig. 16). The surface of Mars is covered by numerous craters (after the photo-

graphs were specially treated and studied 600 craters of different sizes, from 2.8 to 180 km in diameter, were observed on them). The circumpolar regions are covered with a layer of snow, probably frozen carbon dioxide known on the Earth as dry ice. Above the southern polar region, methane and ammonia were found in the atmosphere; it is possible that these gases are of biological origin. Kiss believes that the atmosphere of Mars contains nitric oxide, NO.

It is of interest that the presence of an atmosphere on Mars was proved by comparing the size of the planet as photographed in red and blue light. In blue light, Mars seems to be larger because the atmosphere dispels the blue part of the spectrum of sunlight to a greater degree than the red part.

The possibility of the formation of organic compounds under the conditions prevailing on Mars is of the greatest interest because the answer to this question is necessary for judging whether any forms of life exist on this planet neighbouring ours.

In the spectrum of infrared rays reflected from the dark regions of Mars there have been observed three bands of wavelengths of 3.45, 3.58 and 3.68 μm , respectively. These bands are attributed to C — H bonds and it is supposed that they denote the presence of organic molecules such as carbohydrates. It is possible that the bands are due to the presence of acetaldehyde; their stability indicates the constant regeneration of acetaldehyde. Hence, the conclusion was drawn that metabolic processes occur on the surface of Mars; hydrocarbons are oxidized to aldehydes and alcohols just as they are on Earth where such processes are catalyzed by enzymes.

The assumption that the source of the bands is of a biological nature should be judged critically. A number of authors believe that organic compounds appear

on the surface of Mars as the result of various syntheses occurring in the atmosphere of the planet under the action of ultraviolet rays. In order to check this hypothesis, they decided to carry out experiments in the laboratory simulating the conditions under which acetaldehyde would be exposed to radiation on Mars.

250 μ l (microlitres) of acetaldehyde containing a certain quantity of the ^{14}C isotope were placed in a quartz tube which was then sealed, cooled in liquefied nitrogen and exposed to ultraviolet rays during 24 hours. After that, the tube was opened and various sugar-carriers (glucose, ribose and others) were added. The introduction of labelled (radioactive) carbon facilitated the analysis of the reaction products obtained in very small concentrations, of course. The analysis was conducted by means of chromatographic separation. The reaction products were distributed on a sheet of paper for chromatographic analysis and were detected, after appropriate treatment, by radiation from the radioactive isotope. The radiation was recorded with the aid of a photographic film on which the sheets of paper containing the reaction products were placed. This tracer technique is called autoradiography. It is a very sensitive method because the rays act on the film during a long period of time. In the tests carried out by Ponamperuma the paper remained in contact with the film during three weeks. The non-radioactive carriers can be fixed on the paper with the aid of special reagents.

If acetaldehyde were converted into any carbohydrate, the carbohydrate would be radioactive and by its location on the paper (recorded on the autoradiograph) the particular hydrocarbon could be determined at once (each of the sugar-carriers has its own absorption zone on the paper). Test results showed that the exposure of acetaldehyde to ultraviolet rays gives rise

to the formation of ribose, desoxyribose and some other carbohydrates.

Subsequently, a chamber was constructed in which the investigators simulated the surface of Mars. The chamber contained limonite sand (model Martian soil containing a large amount of iron oxides). The temperature in it was varied from -70 to $+30^{\circ}\text{C}$; a pressure of about 65 mbar was maintained in it; the "atmosphere" in the chamber was composed of 65 per cent CO_2 , 33 per cent N_2 , 2 per cent acetaldehyde and a very small quantity of water. During the day the chamber was exposed to radiation from three ultraviolet lamps emitting rays, chiefly of a wavelength of 2537\AA .

The limonite samples were periodically taken out of the chamber and analyzed. The tests showed that pentoses, hexoses and polysaccharoses were formed in the chamber. It is still necessary to solve the riddle: where did the initial acetaldehyde come from on Mars?

By means of special tests, scientists have ascertained that acetaldehyde can be obtained (it is true, in very small quantities) as a product of the photochemical reaction between water vapours and carbon dioxide under conditions corresponding to those in the atmosphere of Mars.

There is, however, evidence that the formation of acetaldehyde occurs in the dark regions of Mars. This is hard to explain and it is possible that the synthesis of acetaldehyde is associated with the activity of vegetation. Thus, indirectly, both the simulated experiments and observations confirm the possibility of the existence of some forms of life on Mars.

Mars is the last of the inner planets. In far-distant space there is Jupiter at a distance of about 780 million km from the Sun; still farther, the planets Saturn, Uranus, Neptune and Pluto. They resemble each other,

but to our regret, our information about their nature is very inadequate.

The spectral analysis of Jupiter, Saturn, Uranus and Neptune has shown that in their atmospheres intense absorption of light is observed in the yellow, red and infrared parts of the spectrum, absorption increasing from Jupiter to Neptune. Uranus and Neptune seem to be yellow-green even when observed in a telescope; the red and infrared regions of the spectrum are "filtered out", to a large measure, by the planets' atmospheres. What molecules are present in the atmospheres of these giant planets? The study of Saturn has shown that there are no puzzling absorption bands in the spectrum of its ring. Hence, absorption takes place in the atmosphere and its cause is the presence of some gaseous substance. Under Earth conditions no substance gave such bands, and it took more than half a century to solve the puzzle of the mysterious marks in the absorption spectrum. The problem was cleared up only in 1932 when as the result of theoretical and experimental investigations it was established that the absorption bands pertained to methane and ammonia. Both methane and ammonia are well known but the above-mentioned bands are observed in the spectrum of these gases only under the condition that light travels a very long way in the gas. In 1935 Edel and Slipher showed that the intensity of the absorption bands characteristic of Jupiter and Saturn (to be more exact, the intensity intermediate between that of the bands of Saturn and Jupiter) is attained when a ray of light passes through a column of methane 14 m long at a pressure of 40 atm.

Ammonia was found only in Jupiter and Saturn; it was not found in the spectra of Uranus and Neptune. It is supposed that due to the low temperatures on these planets ammonia is in the solid (frozen) state.

Investigation of the infrared part of the spectrum of the giant planets revealed the presence of hydrogen (and also deuterium) in Jupiter, Saturn, Uranus and Neptune (undoubtedly there is helium as well).

Jupiter, surrounded by satellites, is very beautiful when observed in a telescope. Coloured cloudy streaks and spots are visible on its surface; since the planet rotates quickly on its axis it is flattened at the poles and bulges at the equator. Jupiter has constantly attracted the attention of astronomers but it is hard to find another celestial body near us that has been the object of more controversy than this strange planet.

The assumption that Jupiter resembles the Earth was quickly rejected. Neither were the early theories in which Jupiter was regarded as a burning hot body confired. In their place came the views according to which Jupiter is an enormous and very cold mass consisting of a small hard core surrounded by a layer of ice and a very thick atmosphere with clouds of solid carbon dioxide. However, when in 1952 Jupiter passed in front of the star σ -Aquila, investigation showed that light gases, mainly hydrogen and helium, predominate in the atmosphere of the planet.

It was even questioned whether, in general, Jupiter could be regarded as a planet. Indeed, judging by certain features, this giant rather suggested a star. The composition of the gases surrounding it is close to that of gases surrounding the Sun. It is just possible that Jupiter is a "miscarried" Sun. The fact that it is smaller in size than the Sun is the reason why the mass of the planet on condensing did not become hot as the Sun did¹.

¹ Below, the influence of the size of a star on its fate will be discussed in detail.

Each year theoretical and experimental investigation of this planet is being carried out on a larger scale. Above, mention has already been made of the theoretical calculations of the composition of atmospheres in which the authors proceeded from the assumption of chemical equilibrium in the atmosphere. Calculations made for Jupiter were checked by experiments simulating the conditions which exist on the planet. It was of particular importance to ascertain whether organic compounds could exist on Jupiter. This supposition was fully confirmed. A mixture of methane and ammonia was exposed to a corona discharge as a result of which acetylene, ethylene, ethane, hydrogen cyanide and methyl cyanide were obtained.

States of equilibrium correspond to the presence in the upper layers of clouds of hydrogen 0.60 parts by volume; inert gases, 0.39; methane, 0.005; ammonia, 0.0002; water, 10^{-6} . At great depths at a pressure of 1000 atm and a temperature of 350°K , the water content increases approximately 100 times; the content of the other constituents remains unchanged.

According to other data the composition of Jupiter's atmosphere is as follows: 60 per cent hydrogen, 36 per cent helium, 3 per cent neon, 1 per cent methane, 1 per cent ammonia. As can be seen from this data, hydrogen and helium predominate in the atmosphere of Jupiter, while there is comparatively little methane and ammonia.

Of interest are the calculations and results of tests, carried out in a simulated Jupiter atmosphere, concerning high-molecular compounds. It was found that complex molecules of high-molecular mass tend to form even under the conditions prevalent on Jupiter. Some of the high-molecular compounds in a plasma discharge in the simulated atmosphere are coloured (pyrene, coronene), some are fluorescent (chrysene).

The bright colouring of the zones and spots in the atmosphere of Jupiter is probably associated with the formation of organic molecules.

The dense and very thick atmospheres of Jupiter, Saturn, Uranus and Neptune also contain hydrogen cyanide, nitrogen peroxide, NO_2 , in the form of N_2O_4 , water, and, perhaps, hydrogen sulphide. It is possible that the clouds on Jupiter consist of solid crystalline ammonia or its compounds with other substances. The temperature of Jupiter's atmosphere is equal to about 102°K and varies peculiarly with height. Above the layer of heavy clouds the temperature is about 110°K but it grows as the distance from the planet increases, then it falls and increases once more. At a height where the density is equal to 10^{12} molecules/ cm^3 , the temperature is 300°K ; below that at a density of 10^{14} molecules/ cm^3 , it is only 150°K . The temperature of Saturn is equal to about 120°K .

On discussing this variation in temperature and comparing the properties of the gases found on Jupiter it has been assumed by a number of scientists that the inner parts of the planet have a very high temperature (of several thousand degrees). The energy required to maintain this temperature is evolved during radioactive decay. Above the heated zone there is something like a shell composed of oxides of metals, and still higher is the cold zone.

There is another hypothesis developed by V. Fesenkov, A. Masevich, V. Markus, and V. Ramsey, which, although at first sight may seem improbable, is physically well-founded and has many supporters. As is well known, at very high pressures the electron shells of atoms overlap and even substances that do not have metallic properties under ordinary conditions come to resemble metals. The pressure in the inner regions of Jupiter, according to available data, must

be great. It is supposed that it reaches 2 million atm at a depth of the order of $1/5$ of the distance between the top of the clouds and the centre of the planet. Hydrogen and helium at such degrees of condensation pass over to a metallic state.

In the central part of the core of the planet the pressure increases to 40-100 million atm¹. The gas mixture acquires the properties of a solid body. Metallic hydrogen under these conditions has a density 6 times greater than that of water; and helium, almost 13 times that of water. The temperature of the core of Jupiter is measured in thousands of degrees. In the region that is at a distance of 54,000-60,000 km from the centre of the planet, at a pressure from 1,000,000 to 200,000 atm, hydrogen and helium are in the liquid state; and finally, still higher (70,000 km from the centre) is the gaseous layer. In the outer region where the pressure is only 1 atm, the temperature is about 107°C.

It has been proved that the atmosphere of Jupiter is in constant motion and is stirred by powerful currents not only in the horizontal direction but in the vertical one as well. It would not be easy for future space travelers if they took the risk of plunging into the atmosphere of Jupiter in windy weather. The velocity of the wind there attains a value of 500 km/h and constant storms scatter cold clouds of ammonia all over the gloomy planet. There is a mysterious red spot floating in Jupiter's atmosphere: it is the Great Red Spot having a period of rotation about its axis of about 10 h (Fig. 17). Once every two years (on the average) this "spot" meets with a region occupied by an atmo-

¹ 40 million atm in the "hot" model of Jupiter and 100 million atm in the "cold" model.

spheric disturbance (the South Tropical Disturbance) of the nature of which nothing is known as yet. Several hypotheses have been suggested concerning the nature

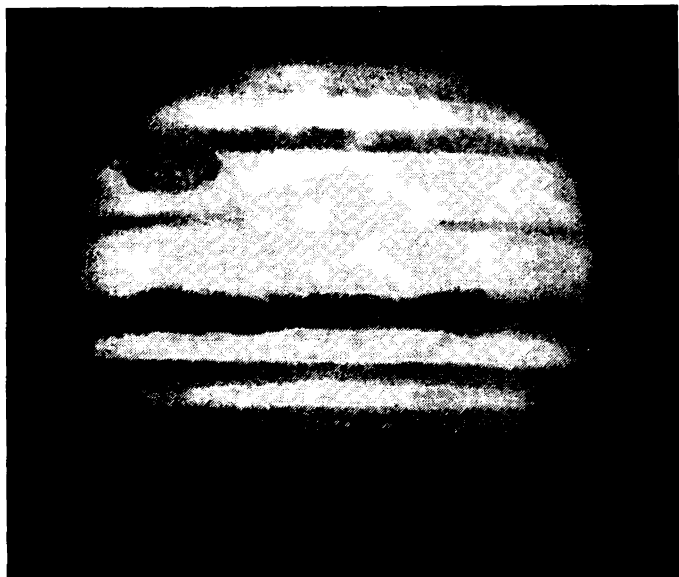


Fig. 17. Jupiter; in the upper left-hand corner is the Great Red Spot

of the Great Red Spot. The investigations and calculations of V. Trubitsyn have shown that the Red Spot is a vast whirlwind that developed in Jupiter's atmosphere. The duration of the existence of this turbulent motion is very great (presumably of the order of a million years); observations conducted from the Earth are going on for 300 years, and during this relatively

short period of time no noticeable changes in the state of the turbulence have occurred.

One of the puzzling features of this strange planet is the vigorous emission of radio waves. Jupiter emits radio waves ranging from centimetres and decimetres to decametres. These emissions of astonishing intensity are associated with mysterious phenomena in the atmosphere and indicate violent explosive processes in Jupiter's upper layers.

Scope of Earth and Space Chemistry

1. GENERAL

In the preceding chapter we came to the very important conclusion that the chemical elements on the Earth and those in outer space are identical. The same laws govern the chemical reactions in a test tube, a plant reactor or in unbounded space containing billions of galaxies! This justifies the next step — the attempt to ascertain what chemical processes actually take place in outer space. To solve this problem, it is imperative to know the conditions characteristic of the planets, stars and the interstellar medium.

Let us assume that the researcher mentally leaves the Earth and is carried away into space. He will encounter, first of all, an extremely rarified medium containing only tens of atoms in 1 cm^3 .

Near the large celestial bodies the number of atoms is greater, of course; but still, on the average, it is very small. Beyond the solar system the space traveler can come across a small but very dense star of the class of dwarfs. He will be very glad that he is travelling only in his imagination! The stellar matter is so greatly condensed that the gravitational forces reach an amazing value: 1 cm^3 of stellar matter weighs about 8 tons! If a man actually found himself on the surface of a dwarf, he would immediately be crushed by his own weight.

At the present time there is data available that indicates that this density is not the limit; there are

stars with a greater density, even millions of times as great.

Let us avoid, for the time being, these dangerous celestial bodies and direct our traveller to the very large and luminous stars, the red giants. The density of these stars is very low, only $1.6 \times 10 \text{ g/cm}^3$, i.e., about a thousand times less than that of air in our Earth!

Thus, in the world of stars the density varies vastly: from almost complete vacuum to such enormous magnitudes as have never been investigated under Earth conditions. Hence, it is necessary to study the behaviour of matter and the peculiarities of space reactions in vacuum and at very high pressures, otherwise it will not be possible to understand the chemical and physical processes in outer space.

But that, by far, is not all. The traveller would naturally have some measuring instruments with him, in particular a thermometer. We shall not try to guess just how the thermometer is designed but like the voyage itself, it is an imaginary one and therefore without any faults: the range of temperatures which it can measure varies from absolute zero to hundreds of millions of degrees (in fact, now there are methods for measuring such high temperatures so that such data can be actually obtainable and not mere fantasy; the instruments used, however, do not resemble ordinary thermometers). In the interstellar medium the thermometer will show its own temperature — it will absorb radiation from the Sun or any other star¹ and

¹ In boundless outer space streams of radiation from many billions of stars intersect, but of special interest is radiation of a wavelength of 0.1 cm ("relict" radiation). We'll speak of it once more at the end of the book. This radiation carries an energy corresponding to a temperature of about 3-4°K. Its appearance is associated with the origin of the universe.

give energy to the atoms in the interstellar medium. When equilibrium is reached, i.e., when the amount of absorbed energy and that released per unit time are equal, the temperature of the thermometer will be constant; it will depend on the physical properties of the material the thermometer is made of.

As we already know, the temperature of the outer layers of the Sun is equal to about 6000 °C, while the temperature in the Sun's interior reaches up to 15 million degrees; these conditions have been obtained on the Earth only recently and only for a very short period of time.

In the Galaxy the traveller would encounter various types of stars, among them the blue giants in the interiors of which the temperature is 10^9 °K. Very little is known about the state of matter under such conditions, and the program of space chemistry research must include the study of substances and their reactions at very high temperatures, right up to billions of degrees!

The measurement of density and temperature does not exhaust the possibilities of physics. Let us supply the traveller with instruments for investigating the nature of the radiation and the strength of the magnetic and electric fields; guarantee him eternal life. Then he will find out that outer space is permeated by streams of radiation containing elementary particles and electromagnetic waves of various length; he will learn that powerful magnetic fields arise and move in space and that sometimes explosions of extraordinary strength occur there — mysterious flares after which new atoms appear, especially atoms of heavy elements. He will notice that in outer space hydrogen and helium atoms are distributed everywhere and will probably draw the conclusion that the life, evolution and explosions of stars are closely connected with the origin of

atoms of the elements and their conversion to each other, i.e., with nuclear reactions. It follows from this that in order to understand the fundamentals of space chemistry it is necessary to study the effect of pressure, temperature and radiation on matter and to ascertain the possibility of the occurrence not only of ordinary reactions but of nuclear reactions as well.

Let us begin the study of the fundamentals of space chemistry with a discussion of the influence of high pressures and temperatures on matter.

2. WHAT HAPPENS TO MATTER AT HIGH PRESSURE

Let us ascertain the effect of a gradual increase in pressure, assuming that the initial state of matter was gaseous. As long as the gas is rarified (at a pressure of the order of 1 atm or less), in accordance with Boyle's law, at a constant temperature the volume of a gas varies inversely with its pressure. Then at a pressure of the order of tens and hundreds of atmospheres the effect of the volume of the molecules themselves is distinctly manifested, and the volume of the gas decreases a smaller number of times than the pressure increases. Let us assume that the temperature of the gas is below the critical one, then at a definite pressure the gas will begin to condensate to a liquid. If the temperature is higher than the critical one, the gas will remain in the gaseous state but its density and viscosity will grow steadily as the pressure increases.

Let us increase the pressure to thousands and tens of thousands of atmospheres (at the present time, high-pressure techniques make it possible to obtain pressures of hundreds of thousands of atmospheres). Such high pressures bring the atoms in solid bodies closer to each other and cause rearrangement of their crystal

lattice. Thus, graphite at high pressures is converted to diamond; silicon dioxide is converted to a very dense variety of SiO_2 ; boron nitride changes its structure and is converted from the hexagonal form to the cubic one of extreme hardness (borazon); new varieties of quartz appear, which retain their acquired structure even after the pressure is removed (L. Vereshchagin, S. Stishov and S. Popova), etc. High pressure produces, moreover, another very interesting effect. It makes the electron shells of atoms react with one another so that the atoms in a crystal will come to have common valence electrons. This, as is well known, is characteristic of the structure of metals. Hence, extreme compression of matter results in the appearance of metallic properties in it. As a matter of fact phosphorus, for instance, at very high pressures displays high electrical conductivity; at first it resembles a semiconductor and then a metal (black phosphorus).

H. Drickamer believes that when the initial volume of solid bodies is reduced by 50 per cent, they become metallic. He claims that such metallization of certain simple substances corresponds to a pressure of the order of hundreds of thousands of atmospheres (135,000 atmospheres for selenium; 250,000 for iodine; 400,000 for sulphur).

Hundreds of thousands of atmospheres, however, are not so much for celestial bodies. What happens if the atoms are under conditions when the pressure reaches many millions of atmospheres? At a high pressure even the density of hydrogen, which under normal conditions is equal to 9×10^{-5} , is increased hundreds of thousands of times and becomes equal to 6 (at 40 million atmospheres).

Theoretical analysis shows that at pressures of hundreds of millions of atmospheres the nuclei and electrons must begin to react with each other. With

very high degrees of compression the protons and electrons unite to form neutrons. The existence of stars whose density exceeds that of the white dwarfs millions of times was predicted by V. Ambartsumyan and G. Saakyan who supposed that the explosions of such neutron stars initiated the process of formation of new stars. In 1958, in the observatory at Mount Palomar a photograph was obtained of an explosion of a neutron star, which proved the validity of the assumption made by Ambartsumyan and Saakyan. With even greater compression, the density reaches a magnitude of the order of 10^{15} g/cm³.

Thus, the density of matter in outer space can vary from 10^{-22} (and even less) to 10^{15} g/cm³. With such a tremendous increase in pressure, simple processes in which gas molecules unite pass over to complex nuclear and nucleon reactions.

From Boyle's elementary law that is known to every schoolboy and schoolgirl we must turn to the theory of interaction of elementary particles — one of the most difficult branches of modern physics in which there is much that is not clear as yet.

Perhaps, rather than the magnitudes of the physical values (the vast distances, high temperatures, etc.), it is the wide scope in which these values vary that makes the greatest impression on those who study the conditions in outer space.

On passing to the influence of temperature on reactions in space, we'll once more be convinced of the significance of this scope for the character of the physico-chemical processes which occur there and see that an increase in the temperature of celestial bodies also results in a transition from ordinary chemical reactions between molecules and atoms to nuclear processes.

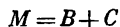
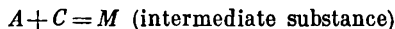
3. WHAT HAPPENS TO MATTER AT HIGH TEMPERATURES

Let us assume that the initial temperature is very low. Nothing hinders us from taking it to be absolute zero; it is physically impossible to obtain a temperature equal to exactly absolute zero, but in special laboratories it is already possible to attain temperatures that differ from absolute zero only by hundredths of a degree. At such temperatures the energy in bodies is close to the minimum one; the electrons are at the very lowest energy levels; their energy and the energy of the body as a whole, although not equal to zero, are of the smallest possible value. Heating of the body leads to an increase in the energy of atomic vibration.

As a result of the distribution of the kinetic energy among the vibrating particles in solids or the molecules of gases, surplus energy is imparted to some of the particles for a short period of time, and they become more chemically active. This process is of very great significance because it is due to it that the temperature influences the rate of a chemical reaction. S. Arrhenius, as is known, supposed that a chemical reaction between two molecules can proceed only if the colliding molecules have an energy that exceeds the average value of the energy of collision. The surplus energy is called the energy of activation; it determines to a great extent the rate of reaction. If the activation energy is equal to zero, any impact results in a chemical change and the reaction proceeds quickly. Thus, for example, when H^+ ions collide with OH^- ions, i.e., in neutralization, electrostatic attraction adds the necessary energy, and neutralization takes place instantaneously. The greater the energy of activation, the slower the chemical change proceeds.

For most reactions, it is necessary to add from 30 to 50 kcal per 1 mole of substance for the reaction to

proceed. Catalysts accelerate a chemical reaction, as a rule, because they reduce the activation energy by causing the process to proceed in a different way. Indeed, whereas, for instance, the process $A \rightarrow B$ requires a high energy of activation and therefore proceeds slowly, processes carried out with a catalyst, i.e., involving the chemical changes:



are generally other reactions that are characterized by smaller activation energies. Some catalysts reduce the activation energy to 10-15 kcal/mole; enzymes even to 1.5-5 kcal/mole.

If it be taken into account that in the mathematical expression of the dependence of the rate-of-reaction constant k on the energy of activation E , the latter is in the exponent:

$$k = k_0 e^{-E/RT}$$

where k_0 = a constant

e = base of the natural logarithms

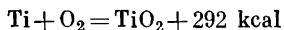
R = gas constant

T = absolute temperature

it is not difficult to realize that even a small change in the activation energy strongly affects the rate of reaction.

It is worthwhile to glance at the equation once more. If we look at the exponent, we'll note that formally an increase in the temperature (T) has the same effect as a decrease in the activation energy (E). Practically, however, it is frequently better to lower the activation energy (for example, with the aid of a catalyst) than to heat the substance. On heating a substance strongly various secondary reactions (which do not occur at lower temperatures because of the high activation energy) can take place simultaneously.

When we pass over to temperatures characteristic of stars, reactions with very high E values can take place. On the other hand, high temperatures favour a shift of the equilibrium in the direction of the formation of endothermic products. If the reaction for the formation of titanium dioxide is accompanied by the release of energy:



it is obvious that the reverse reaction will be accompanied by the absorption of heat; therefore the shift in equilibrium to the left is possible only on condition that the compound is strongly heated. With stellar temperatures the dissociation of even very stable compounds such as the oxides of metals can be expected.

There is another class of compounds that can be found under the conditions of outer space — these are also unstable and active forms of matter resulting from the action of high temperatures or radiation, i.e., free radicals. Radicals are atoms or groups of atoms containing unpaired electrons. Thus, for example, the hydrogen atom and sodium atom are radicals. The oxygen atom even has two unpaired electrons and belongs to the class of biradicals.

The presence of unpaired electrons (usually designated by a dot over the formula of the radical: $\dot{\text{H}}$, $\dot{\text{Cl}}$, $\dot{\text{O}}\dot{\text{H}}$) is the reason for high chemical activity: the radical strives to gain the second, missing electron. On acquiring the second electron, a more stable distribution of electrons (a more stable configuration) is attained.

That is why two atoms of hydrogen combine to form a molecule H_2 ($\text{H} : \text{H}$), the Cl radical unites with a Na radical to produce sodium chloride, NaCl ($\text{Na} \quad \text{Cl}$), etc.

Such radicals react readily and therefore exist in the free state only for a very short time, often only fractions of a second. Complex radicals consisting of several atoms live longer. Some of them can exist in the free state for an indefinitely long time. When solid bodies are cooled to very low temperatures even active radicals can be frozen in them. The core of comets consists of solid masses of substances, in particular water, containing various radicals in the frozen state. On the other hand, such radicals as CH_3 , C_2 , CH , CH_2 are present in gases at high temperatures. These are the blocks from which, on cooling, more complex molecules can be formed. Perhaps the first stages in the chemical evolution on our Earth consisted in various transformations of radicals. The activation energy of such reactions is not very great and sometimes is practically equal to zero. Such reactions, therefore, proceed rapidly.

4. PLASMA STATE OF MATTER

If a substance is heated until its temperature reaches hundreds and thousands of degrees, a process of intense ionization ensues. The atoms lose their outer electrons, and the mixture of ions and electrons is formed, which is known in physics as plasma. The temperature of plasma is not expressed in degrees but, preferably, in electron volts, i.e., in units of energy since energy is proportional to temperature. 1 eV corresponds to a temperature of 11, 600° C. Hot plasma has a temperature of hundreds of electron volts (millions of degrees). Plasma possesses peculiar properties. It cannot be kept in any vessel because all materials disintegrate and are ionized at such high temperatures but it can be retained by a magnetic field. The motion

of plasma particles depends considerably on the magnetic field acting on the plasma; the particles rotate around the magnetic lines of force and, consequently, the field can cause powerful currents to arise within the plasma.

The plasma state is one of the most unstable states of matter. It is extremely difficult to retain plasma in a steady state to study its properties; to retain stable plasma during hundredths of a second is considered a major achievement. Soviet scientists obtained plasma with a temperature of about 40 million degrees and retained it in their apparatus for hundredths of a second, attaining a density of 10^{10} particles per 1 cm^3 .

Plasma is a so-called quasi-neutral medium. In plasma the positive and negative charges are distributed in such a way that considerable separation of charges will not occur in space. If this could happen, great forces would arise striving to equalize the average concentration of positive and negative charges. Small fluctuations in the concentration of positive and negative charges, however, are possible. As soon as positive and negative charges are separated, something like a capacitor with oppositely charged plates appears. There is an electric field between the plates, and the motion of an electron in it is accelerated. The accelerated motion of a charge gives rise to electromagnetic oscillations. It can also be said that the separation of charges in plasma leads to fluctuation in charge density. This is called plasma fluctuation; it is an important characteristic of plasma. Other kinds of fluctuation of plasma are possible, but the one described above is the simplest of all.

Plasma is capable of emitting electromagnetic waves. The Sun's red-hot mass is hydrogen-helium plasma and radiates waves of different lengths: from very long waves (in the region of radio waves) to very

short ones¹. Lately, important data has been obtained on the X-ray radiation of the Sun, stars and planets (e. g., Jupiter). Plasma is the basic form of existence of the great masses of matter in outer space. In hot plasma special reactions take place — it is the sphere of nuclear chemistry. At a temperature of a million degrees molecules cannot exist, whereas atomic nuclei acquire such a high energy that on colliding with each other, they can produce new nuclei. Under conditions prevalent in hot plasma the conversion of elements to different ones is quite possible.

Evidence that the nuclei of certain atoms are capable of disintegrating and liberating enormous amounts of energy was obtained in the laboratories of A. Becquerel and P. and M. Curie, where the scientists encountered the phenomenon of radioactivity for the first time. Later, methods were found by which nuclei could be made to interact and change their charge and mass, i.e., to convert an element into another one!

It was found that the sum of the masses of the original nuclei was generally not equal to the sum of the masses of the nuclei resulting from the reaction. If the sum of the masses of the initial particles is greater, energy is released in an amount equal to $E = \Delta mc^2$ where Δm is the change in mass and c is the velocity of light. The energy effect of nuclear reactions is great; it exceeds the effect of ordinary chemical reactions millions of times.

It can be stated with certainty that space chemistry is basically nuclear chemistry. Calculations show

¹ Investigations of the Sun's short-wave and X-ray radiation became possible after instruments could be lifted to the upper layers of the Earth's atmosphere with the aid of special rockets. At the present time it has been proved that heavy ionized atoms, in particular iron ions, are the source of solar X-ray radiation.

that no ordinary chemical reactions can give so much energy as, for example, is needed to maintain the temperature of our Sun. But the Sun is only one of many stars. The problems concerning the Sun are the general problems of stellar physics and chemistry — comparatively new branches of knowledge, the future development of which is veritably limitless.

The World of Stars

1. BRIGHTNESS AND LUMINOSITY OF STARS

The stars are not spread evenly throughout the universe. They are bunched together in galaxies; the latter, however, are scattered in space rather uniformly.

There are billions of stars in the Earth's galaxy and the number of galaxies is just as large. The visible part of the heavens contains 10^{21} stars (according to Korkiss). Light from the nearest stars travels for several years to reach the Earth (about 4.2 years from our nearest neighbour: Alpha Centauri). It is very difficult to measure stellar distances. It is necessary to make assumptions that astronomers do not believe to be well-grounded. Thus, it is assumed that for each star type (variable stars or Cepheid variables; blue stars or the blue 'giants') brightness depends only on distance and knowing the distance to one of them the distance to another one farther away is calculated by the decrease in brightness.

If, mentally, the stars were placed at the same distance (in stellar astronomy the standard distance is taken to be equal to 10 parsecs), then brightness can serve as a comparative characteristic of stars. The brightness at the standard distance is the absolute magnitude of a star. The total radiant energy emitted by a star per unit time is called luminosity; this characteristic gives more information about the state of a star

than brightness does. Generally, the unit of luminosity is the luminosity of the Sun. The range in which luminosity varies is very large — from hundreds of thousands of “luminosities of the Sun” (supergiants) to thousandth parts of this unit (dwarfs).

Table 6

Characteristics of Certain Stars (According to Gavrusovich)

Star	Pressure, atm (in centre)	Temperature, °C (in centre)	Energy emitted, erg/g per s (luminosity)
Sun	10^{11}	$19 \cdot 10^6$	2
Sirius	10^{11}	$26 \cdot 10^6$	30
Capella	$8 \cdot 10^7$	$6 \cdot 10^6$	50
α -Standard-bearer	$3 \cdot 10^{10}$	$25 \cdot 10^6$	180
γ -Cygnus	$3 \cdot 10^{10}$	$32 \cdot 10^6$	1200

2. THE HERTZSPRUNG-RUSSELL (HR) DIAGRAM AND STELLAR EVOLUTION

Stars are not eternal, and the universe is not static as one might suppose when looking at the sky on a clear evening. It appears to be so permanent and invariable: the twinkling of the stars seems to say that thousands of years ago everything was the same as now and will remain the same when new thousands of years will pass. As a matter of fact the case is somewhat different. Though it is true that a hundred, a thousand and even a million years is a very short time on a cosmic and stellar scale, still stars do change in the course of time. They are born, live; when they are young, the processes in the star's interior proceed intensively;

then they begin to degenerate and finally die; sometimes after dying, they explode which is the beginning of a new stage in the conversion of the stellar matter.

Relatively high temperatures and low densities are characteristic of young stars. Towards the end of its life a star becomes smaller in size and its density increases until it becomes a very dim white dwarf.

Stars differ in surface temperature. In stellar classification stars are denoted by the letters O, B, A, F, G, K, M. A surface temperature of $50,000^{\circ}\text{C}$ is characteristic of class O; a temperature of about $28,000^{\circ}\text{C}$, of class B; class A has a temperature of $10,000^{\circ}\text{C}$; class F, 7700°C ; class G (specifically, our Sun), about 6000°C ; class K, 5000°C and class M, 3800°C .

It has been proved by a large number of observations that there is a direct relationship between the luminosity, and accordingly the absolute magnitude of a star, and its spectral class. Since the class of a star also corresponds to a definite temperature, the latter is likewise plotted on the diagram in order to show this dependence. Figure 18 presents a diagram plotted on the basis of the study of the states of a very great number of stars. The diagram was proposed by E. Hertzsprung in 1907 and, independently, by H. Russell in 1914.

E. Hertzsprung and H. Russell discovered that for stars of a given type an increase in mass is accompanied by an increase in luminosity. Hence, on the diagram in the upper right-hand corner are points showing the state of stars of enormous mass, high luminosity but relatively low surface temperature. These are the giants; they are subdivided into supergiants, giants and subgiants. Along the diagonal and in the lower left-hand corner, respectively, appear the subdwarfs and white dwarfs (the latter will be discussed below); their mass is smaller than that of the Sun. The majority of

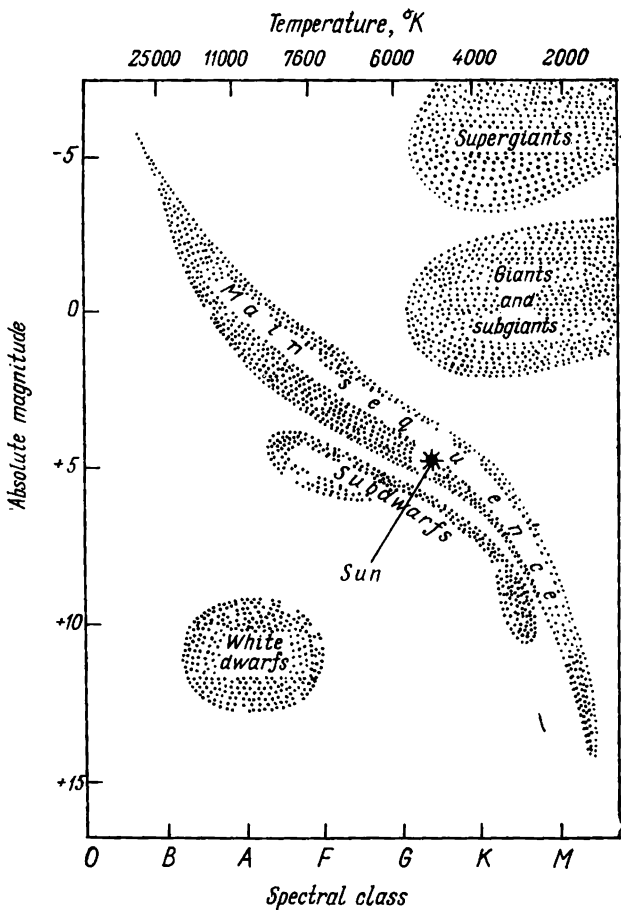


Fig. 18. The Hertzsprung-Russell diagram

points, i.e., the greatest number of stars, fall on a straight line that runs diagonally across the diagram from upper left to lower right and is called the main sequence. Our Sun appears in the central part of the main sequence; the very hot, highly luminous stars appear at the upper left, small relatively cold and dim stars appear toward the lower right.

A remarkable feature of the HR diagram is that one can trace the entire life history of a star on it, from its birth to the final stage in its evolution. The stars in the course of their life appear to move along the main sequence from left to right. Moreover, we learn that each new stage in the evolution of a star corresponds to chemical changes in its composition, which in fact, are the reasons for its appearance: the diagram illustrates the relationship between the chemical conversions and the stages in the development of stars.

Stars from their birth to their death or explosion pass through stages which are reflected in this diagram to a greater or smaller degree. It all begins with the condensation of a cloud of gas and dust and the formation of starry nuclei that are denser than the surrounding medium. This stage is observed in galactic systems. Then gravitational forces compress the star. The stellar matter is heated and begins to radiate light. These processes correspond to the motion of stars on the HR diagram from the right to the left. The star takes its place on the main sequence.

Stars of different mass appear on the main sequence at different points. If a star has a large mass, it will be heated to a very high temperature earlier than equilibrium between the gravitational forces and the radiation pressure is reached. Such a very hot star will appear on the main sequence nearer to the upper left than stars with a smaller mass. It takes millions of years

for a star to approach the main sequence, and it remains on it for billions of years.

Finally, the star exhausts all the nuclear fuel in its interior where the temperature is the highest and where matter is constantly mixed (the zone of convection). The radiation zone surrounds the convection zone; here energy is transported by radiation. The radiation zone passes to the outer zone through which energy is dispersed into the surrounding space.

It is supposed that having exhausted their fuel, the stars begin to contract again as a result of which the temperature at the edge of the radiation zone grows. When it reaches millions of degrees, nuclear reactions occur not in the nucleus but in the radiation zone. The star expands and its outer layers gradually cool off. As a result a huge tenuous mass of gas of a relatively low temperature appears, and the red giant takes its place in the upper right-hand corner of the diagram. The further evolution of these giants with a very large mass exceeding that of the Sun can proceed in different ways that are not indicated on the HR diagram.

3. CHEMICAL COMPOSITION OF STARS

As the temperature rises, the particles capable of existing in the stellar atmosphere are reduced to simpler ones. The spectral analysis of stars in classes O, B, A (having a temperature from 50, 000 to 10, 000° C) shows the lines of ionized hydrogen and helium and ions of metals in their atmospheres; in class K (5000° C) radicals already appear; and in class M (3800° C) even molecules of oxides.

Table 7 gives in greater detail the amounts of individual elements found in class B stars.

The figures given in Table 7 are relative ones. This means, for example, that in the star γ -Pegasus for

Table 7

Chemical Composition of Stars in Class B

Element	Relative number of atoms in star		
	τ -Scorpio	ζ -Perseus	γ -Pegasus
Hydrogen	8530	8300	8700
Helium	1450	1700	1290
Carbon	2.0	1.5	3.3
Nitrogen	3.1	1.7	0.9
Oxygen	11.0	9.0	3.7
Fluorine	—	—	0.028
Neon	4.5	3.4	4.65
Magnesium	0.46	0.49	0.76
Aluminium	0.032	0.05	0.005
Silicon	0.75	0.77	0.094
Phosphorus	—	—	0.0028
Sulphur	—	0.25	0.55
Chlorine			0.014
Argon		—	0.07

every 8700 hydrogen atoms there are 1290 helium atoms, 0.9 nitrogen atom, etc.

Hydrogen and helium lines predominate in the spectrum of stars of the first four classes; but as the temperature falls there appear lines of other elements and even lines which indicate the existence of compounds. These are rather simple compounds, such as the oxides of zirconium and titanium (class M) as well as the radicals CH, OH, NH, CH₂, C₂, C₃, CaH, and others. The outer layers of stars consist mainly of hydrogen; on an average, for every 10,000 hydrogen atoms there are about 1000 helium atoms, 5 oxygen atoms and less than 1 atom of other elements.

There are stars which have a high content of particular elements. Thus, there are stars which have a relatively high silicon content (silicon stars); stars that have a high iron content (iron stars); a high manganese content (manganese stars); a high carbon content (carbon stars), etc. Stars with an anomalous composition are quite varied. A high content of heavy elements has been detected in young stars of the type of red giants. It was found in one of them that the content of molybdenum exceeded the content of this metal in the Sun 26 times. In general, the content of elements whose atoms have a mass greater than the mass of the helium atom gradually decreases as the star grows older. Moreover, the chemical composition of a star depends on the location of the star in the Galaxy. In old stars in the spherical part of the Galaxy, there are few atoms of heavy elements, while in the part which forms the spiral arms of the Galaxy and in its flat part there are stars that have a relatively high content of heavy elements. It is in these regions that new stars are born and that is why the presence of heavy elements can be associated with the chemical evolution characteristic of the life of a star.

The chemical composition of a star depends on two factors: the nature of the interstellar medium and the nuclear reactions which occur in a star during its life history. The initial composition of a star is close to the composition of the interstellar matter, i.e., the cloud of gas and dust, from which the star evolved. This cloud is not the same everywhere. It is quite possible that a star appearing in a certain place in the universe will be, for instance, richer in heavy elements than another one which is formed in a different place.

Spectral analysis of the composition of stars must take into account numerous factors, such as gravitational forces, temperature, magnetic fields. But even with

observing all the rules of investigation, the data seems inadequate: spectral analysis concerns only the outer, surface layers of the star. What is going on in the interior of these far-distant bodies seems to be inaccessible for study. The spectra of stars, however, show unmistakable evidence of the presence of elements which are the products of nuclear reactions (barium, technetium, zirconium) and which can be found only in the star's interior. Hence it follows that stellar matter undergoes a process of mixing. From the point of view of the physicist it is difficult to reconcile the idea of mixing with that of equilibrium of the huge mass of stellar matter, but for the chemist this spectroscopic data constitutes material of inestimable value because it permits well-founded assumptions to be made concerning the course of nuclear reactions in the interiors of celestial bodies.

The analysis of stars in the spherical part of the Galaxy containing the oldest stars shows a low content of heavy metals (according to L. Aller). On the other hand, if the Galaxy did develop from a gas cloud consisting mainly of hydrogen, there must be purely hydrogen stars in it. Such stars include the subdwarfs. They occupy a place midway between the stars of the main sequence and the white dwarfs. In subdwarfs there is a large amount of hydrogen while the quantity of metals is small.

Table 8 (according to L. Aller) gives the logarithms of the ratio of the number of atoms of a given element on the Sun to the number of the same element in subdwarfs (i.e., abundance). As can be seen, the numbers, as a rule, are greater than zero, i.e., the amount of metals in the Sun is greater than that in the subdwarfs.

Evidence of nuclear transformations changing the "features" of the star is sometimes very clear. Thus, there are stars wherein hydrogen was converted to he-

Table 8

Abundance of Elements in Subdwarfs

Element	Abundance	
	HD 140283	HD 19445
Carbon	3.40	2.25
Magnesium	1.87	0.58
Argon	2.73	1.54
Cobalt	2.02	1.37
Scandium	2.34	1.84
Titanium	1.72	1.20
Vanadium	1.76	1.93
Manganese	1.99	1.54
Iron	2.06	1.75
Nickel	1.42	1.53

lium; the atmosphere of such stars consists of helium. Perhaps the mixing of stellar matter played a significant part in the increase in the helium content of the outer layers of these stars¹.

Careful study of one of these stars showed the presence of carbon and neon as well as titanium in them. In another helium star it was found that for every 500 helium atoms there were 0.56 carbon atom, 0.72 nitrogen atom, 1.0 oxygen atom, 3.2 neon atoms, 0.05 silicon atom and 0.5 magnesium atom. A bright bina-

¹ A. Boyarchuk found eight stars in which the content of helium was a hundred times greater than that of hydrogen and for every 10,000 helium atoms there was only one iron atom. One of the helium stars did not contain hydrogen at all. This is observed very rarely and apparently indicates that all the hydrogen was exhausted in the process of nuclear reactions in the star.

ry star in the constellation Sagittarius, a supergiant with a surface temperature of about $10,000^{\circ}\text{C}$, is also a star deficient in hydrogen: in its spectrum helium lines are clearly seen while the hydrogen lines are very faint. Apparently, these are stars that have exhausted all their hydrogen in nuclear reactions; the presence of carbon and nitrogen in them gives grounds for making correct surmises concerning the course of the nuclear reactions that supply energy and produce the nuclei of various elements.

Of great interest are the carbon stars. These stars are comparatively cold (giants and supergiants). Their surface temperature usually lies in the range of $2500\text{--}6000^{\circ}\text{C}$. At temperatures lower than 3500°C , when there is an equal amount of oxygen and carbon in the atmosphere, a great part of carbon and oxygen is present in the form of carbon monoxide, CO . Other carbon compounds found in these stars are cyan (the CN radical) and the CH radical. A small amount of the oxides of titanium and zirconium which are resistant to high temperatures is also present. If there is an excess of hydrogen, the concentration of CN , CO , C_2 will be relatively low and the concentration of CH will increase. Such stars (CH -stars) are encountered along with stars that are deficient in hydrogen.

In one of the stars it was found that the ratio of the carbon content to the iron content was high: the amount of carbon exceeded that of iron 25 times and the ratio of carbon to hydrogen was equal to 40. This means that the star is very rich in carbon and poor in hydrogen. Variation in the brightness of one of the stars of this type was even attributed to reduction in luminosity due to solid carbon particles scattered in the star's atmosphere. A normal hydrogen content, however, is characteristic of the majority of carbon stars (according to L. Aller).

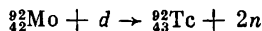
An important feature of carbon stars is their relatively high content of the carbon isotope $^{13}_6\text{C}$. The role of this isotope in the total energy balance of the star is very great. The processes in which it participates supply the star with energy; they occur only at very high temperatures in the interior zones of the stars. The appearance of the $^{13}_6\text{C}$ isotope in the surface layers can, probably, be attributed to mixing.

A high content of metals located in the same subgroup of the periodic system as zirconium is characteristic of a number of types of stars. These stars contain the unstable element technetium, $^{99}_{43}\text{Tc}$. Technetium nuclei could be formed from ^{98}Mo as a result of the capture of a neutron and subsequent loss of an electron from the molybdenum nucleus (see Ch. V, Para 5) or in a photoprocess from ^{97}Mo ¹. In any case the presence of the unstable nucleus affords convincing evidence that nuclear reactions do occur in stars.

Astronomers and astrophysicists have performed an enormous amount of work in analyzing and correlating spectral data and the information procured from meteorites. As a result, a picture of the occurrence of elements in the universe has been obtained. Figure 19 presents the results of this work in the form of a curve showing the dependence of the relative rate of occurrence of an element on its atomic number. The sudden sharp zig-zags and jumps indicate that certain elements are preferred to others in outer space.

This is actually a fact! As has already been stated in the chapter that deals with meteorites, elements with even atomic numbers are encountered in them more

¹ The $^{99}_{43}\text{Tc}$ isotope was obtained artificially by Pierre and Sieger in 1936 by exposing molybdenum to the action of deuterons, according to the equation



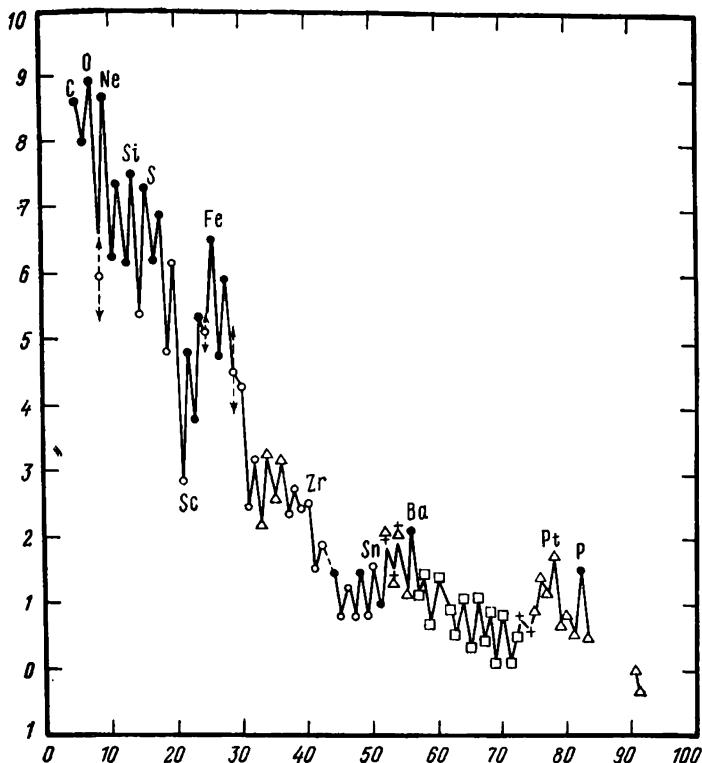


Fig. 19. Abundance of elements in outer space: the atomic numbers are plotted on the axis of abscissas; the logarithms of their content per 10^{12} H atoms, on the axis of ordinates

frequently than those with odd numbers. This is a general rule. Why are elements with an even atomic number preferred? The reason is that their nuclei are more stable; the stability of a nucleus depends on the ratio

of the number of protons to the number of neutrons in it. The most stable nuclei had a better chance of being formed and surviving under drastic conditions.

4. STELLAR ATMOSPHERES. LIGHT AND GRAVITATION

For increasing our knowledge of the nature of the chemical and physical processes that arise in the stars, of special importance is knowledge of the violent stages of stellar life when there is a sharp increase in radiation and temperature and the spectral lines become more distinct. It is only rarely that such stages can be observed and studied but then very valuable information is obtained.

In ordinary periods when stars are in a tranquil state, spectral analysis can also tell us very much because radiation is virtually the only source of information about the far-distant celestial bodies. Fortunately, stars are such powerful sources of radiation that stellar spectroscopy and radioastronomy, as yet, have far from exhausted their latent potentialities.

The hot stars have a very high temperature and luminosity and extensive atmospheres. These stars are enveloped in enormous masses of extremely hot gases which radiate so strongly that the radiation of the star itself, i.e., its surface or photosphere, will not be capable of dimming the radiation of the atmosphere¹. The streams of radiation are so intense that the pressure of light becomes an important factor, which is not, of course, customary for us. Light exerts pres-

¹ The contrary is true of the Sun. Because of the relatively small thickness of the outer layer of the chromosphere, its radiation is feeble and the spectral lines are hardly visible on the background of the bright continuous spectrum of the photosphere.

sure! Although this expression is certain to be familiar to many of the readers of this book, it may seem strange to some of them: less than a hundred years have passed since the time when not only the layman but prominent physicists regarded the idea of light pressure to be devoid of any meaning.

The brilliant experiments of P. Lebedev have proved that light beams are capable of deflecting falling dust particles from their normal trajectory and can set in motion small impellers placed in an evacuated vessel.

Light is absorbed and emitted by atoms in small portions, quanta, the quantum being proportional to the frequency of oscillations of the electric and magnetic forces in the light wave. This important conclusion was drawn by M. Planck in 1900 and constitutes the essence of one of the most well-founded chapters in theoretical physics — the quantum theory. A. Einstein considered light quanta to be particles, photons. This was an acknowledgement of the mysterious dual nature of the behaviour of light: sometimes light behaves like a wave and sometimes (in particular in reactions with atoms) like a stream of particles (i.e., photons or quanta). If a particle has an energy E , then consequently it possesses a momentum P . In accordance with the laws of mechanics the kinetic energy E corresponds to a momentum

$$P = \sqrt{2mE}$$

According to Newton's law a force is equal to the mass multiplied by the acceleration:

$$F = m \frac{\Delta v}{\Delta t}$$

where Δv is the change in velocity in a period of time Δt . If the time is taken to be equal to unity and the

initial velocity to be equal to zero, then

$$F_{(1)} = mv \quad (\Delta v = v - v_0)$$

But the product mv is the momentum P , hence,

$$F_{(1)} = P$$

Pressure is a force referred to unit area. Therefore, if photons possess a momentum, they should exert pressure on the surface of any particle they meet on their path and transfer a respective momentum to it.

Can light resist the force of gravity? Under Earth conditions it does seem impossible to fly off on a light ray. But when a star is formed from an enormous mass of matter, the gravitational forces compress the matter. An increase in temperature finally results in the development of reactions (discussed below in Ch. V) which are accompanied by intense radiation. The extremely hot mass of stellar matter becomes the sphere of action not of gravitational forces which compress the matter but also forces of gas and light pressures that strive to scatter it. Equilibrium of these forces is maintained for a certain period of time but it is unstable due to the fact that the reactions which are responsible for the radiation proceed continuously.

During the life of a star the pressure of ultraviolet rays is such that atoms of hydrogen, helium and other elements are thrown out by the stream of light into the depths of outer space. Some stars (of the type of Wolf-Rayet) which have a temperature from 40,000°C to 100,000°C continuously emit masses of gases. If the radiant particle (for instance, an atom or ion) moves rapidly (the velocity of a particle emitted from a star reaches 2000 km/s), the position of the spectral lines corresponding to this particle is shifted (the Doppler effect). Naturally, the masses of scattered gases contain particles moving with various speeds

and in various directions. As a result, instead of distinct lines in the spectrum there appear bands (the lines are blurred). These bands are characteristic of the Wolf-Rayet stars. The Soviet astronomer N. Kozyrev has shown that such a star can lose in the course of one year a mass of the order of a tenth of the mass of the Sun. The Wolf-Rayet stars are relatively short-lived; at the end of about ten thousand years of violent and extravagant life they will exhaust all their energy resources and their mass will be reduced, their temperature lowered and the emission of gases discontinued.

5. NOVAE

Among the serenely shining stars scattered in the firmament a spectacular phenomenon occasionally occurs. One of the dim stars that was hardly visible suddenly begins to shine more and more brightly. During several days its brightness increases by 10-14 stellar magnitudes, and it becomes hundreds of thousands of times brighter. The dazzling flare, however, rapidly fades away and in the place where the mysterious star had just shone so brightly again a very dim little star appears. Frequently this star was previously unnoticed, and it was supposed that the flare signified the appearance of a new star. The term "nova" is still used in astronomy. In the 2nd century BC Hipparchus observed a brilliant nova in the constellation Scorpio. Evidently it was this unexpected discovery that prompted him to draw up a list of all the stars, indicating their brightness. Thus was the first stellar catalogue compiled; it was an important contribution to progress in the field of astronomy.

Such miracles are not often observed. In Europe novae were observed in 1572 and 1604. Novae are

known to have appeared in 1918 and 1934. They attained the brightness of stars of the first magnitude. In 1901, 1925, 1946 explosions of novae were observed not by specialists but by a postman, a high-school student and a track-walker, respectively.

In general, a considerable number of novae explode in our galaxy — up to two hundred each year, but not all of them are bright enough for detailed analysis.

What is signified by the eruption of a nova? What forces cause an enormous mass of matter to suddenly participate in a mysterious violent process accompanied by the release of a tremendous amount of energy and a sharp increase in the intensity of radiation? Can it be that the Sun (which is a star!) is also subject to such fits of rage? Perhaps mankind should fear that at some tragic moment a powerful avalanche of light from the exploding Sun will burn all life on Earth. Does this danger actually exist? All these questions can be answered only after defining the cause of the explosion of novae and on understanding the physical and chemical essence of the whole process of stellar evolution.

Spectral analysis shows that large masses of atoms are ejected into space; the cloud of atoms is permeated by its own radiation and the Doppler effect gives evidence that the atoms move rapidly in the direction of the observer on the Earth and in the opposite direction. Under the pressure exerted by light the entire atmosphere of the star is stripped from it and spreads out into the surrounding space (E. Mustel). It can be seen as a nebulous cloud distributed around the point where the explosion occurred (Fig. 20).

Repeated explosions result in the loss of matter to space; the star contracts and is finally transformed to a white dwarf — a small and very dense body. From studies of the characteristic changes in brightness which

precede an explosion, it can be concluded that the danger of self-combustion does not threaten the Sun, and mankind has no grounds for worrying about the star that gives life to it.

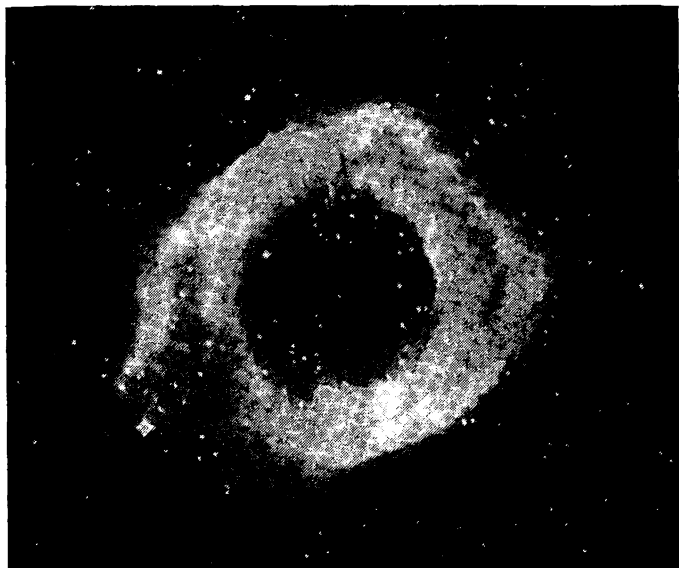


Fig. 20. Ejection of cloud of gas into space. Nebula GC 725

From studies of novae by up-to-date astrophysical methods it has been concluded that they are binary stars. The pair of stars consists of a subdwarf having a high temperature (class B) and a cold dark satellite (class K or M). The satellite loses part of its mass through the point of the binary system at which the gravitational forces are balanced. As a result, a gaseous ring appears around the hot star (gas partially evapo-

rates through the "outer" point of equipoise). The accumulation of hydrogen in the gas ring is accompanied by an increase in temperature, the generation of nuclear reactions and ends in an explosion (the star goes nova).

6. SUPERNOVAE

Sometimes incredibly violent explosions occur — for a short time the star shines like millions and billions of suns. In 1885, a nova appeared in the Andromeda nebula, whose brightness was almost 10 billion times greater than that of the Sun (taking into account the distance to the nebula).

Such stars are called supernovae — they differ from novae not only in brightness but in other attributes as well; in particular, after the spectacular explosion of a supernova its remnants emit radio waves for a long time¹. On July 4, 1054, as recorded in ancient chronicles (Chinese, Arabic and Japanese), a star appeared in the sky (it was called a "visiting star"), which was so bright that it was visible even in the daytime. It shone for 23 days and then it began to decrease in brightness.

In our times examination of the part of the sky where, according to the ancient chronicles, this star had appeared showed that all that has remained of this great supernova is the Crab Nebula (named for its shape). This nebula is rapidly expanding at a rate of about 1300 km/s; two stars can be seen in its centre. The diameter of the Crab Nebula is equal to 6 light-years and the distance to it from our solar system is over 4000 light-years. Calculations have shown that

¹ Yu. Pskovsky, *Novye i sverkhnovye zvezdy* (Novae and Supernovae), "Nauka" Publishers, 1974; I. Azimov, *The Universe*, Walker and Company New York, 1969.

about 800 years ago the entire mass of the nebula was concentrated in its centre. It was then that there occurred the violent explosion which was taken by the observers to be the appearance of a "visiting star" and from that time the nebula resulting from the explosion began to expand. Most astonishing was the extreme violence of the explosion and the intense radiance attained by the stellar matter at the time of the appearance of the nebula. Studies showed that a supernova shines like a hundred million Suns and ejects streams of gas rushing along at a rate of the order of 6000 km/s! At present it has been established that such explosions of supernovae occur in the galaxies once in 400 years (on the average, according to P. Kukarkin).

The explosions of novae and supernovae and the solar flares which occasionally occur on the Sun's chromosphere can cause such an increase in the radiation of cosmic rays that despite the protective properties of the Earth's atmosphere, they can considerably affect life on the Earth. The increase in cosmic radiation is the cause of radio and magnetic disturbances on the Earth, of changes in the weather; it influences the health and the course of diseases of people and animals. It is even supposed that the extinction of certain species of animals (e.g., the dinosaur), which inhabited the Earth before man appeared on it, is associated with the intensification of cosmic radiation resulting from the sudden explosion of a supernovae.

7. COMETS

The spectacular appearance of comets in the sky excited the minds and imagination of observers to an even greater extent than meteorites did. Their enormous luminous tails moved across the whole sky and gave rise to completely false conceptions of the mass

and density of the celestial body approaching the Earth. Scientists have registered the majority of comets one way or another and by 1966, astronomical catalogues contained data on 876 comets.

According to modern data a comet is composed of a solid *nucleus* (core) surrounded by a tenuous mass of gases and sometimes a tail. The solid nucleus is not large — only a few kilometres in diameter (sometimes even much less, only a few hundred metres). The nucleus consists of solidified gases, mainly methane and ammonia (methane-ammonia ices) containing inclusions of mineral particles (from 10 to 30 per cent). As a comet approaches the Sun, its state changes. Heat from the Sun causes the ices to warm up and evaporate. The resulting gases produce the *coma* surrounding the nucleus. Together the nucleus and the coma are called the *head* of the comet. Part of the coma is blown away into a stream behind, to form or increase the comet's tail, always directed away from the sun.

Solar radiation is also responsible for the appearance of active particles called radicals. The spectra of comets indicate that the masses of gases in comets contain the following radicals: CN, CO, CH, CH₂, C₂, C₃. By means of powerful telescopes and spectrographs, evidence has been obtained of the presence in comets of the radicals CO⁺, CO₂⁺, N₂⁺, O₂⁺, i.e., of ions of the oxides of carbon (CO, CO₂), oxygen and nitrogen and also, in a number of cases, of metallic sodium. Sodium can be detected in the tail of a comet at a distance up to 500,000 km.

Nuclear Reactions and Sources of Stellar Energy

The central problem of stellar physics and chemistry is the question of the source of energy that feeds the extremely hot "furnaces" for millions and billions of years. Just as important is the question of what chemical processes are going on in stars. There is every reason to assume that stars form atoms of all the known elements. At the present time there is no longer any doubt that the stars are actually atomic "factories" Radioactive elements, for example technetium, have been observed in the spectra of stars. Technetium is unstable and it should decay and disappear in a very short period of time; hence, its presence in the star's atmosphere indicates that it is being formed in some nuclear process. Moreover, nuclear reactions are the source of energy of the star. That is why we must turn from stars to atoms.

1. CONSTITUENTS OF THE ATOMIC NUCLEUS

In order to understand the processes which take place in the stars it is necessary to study atoms! Perhaps what astonishes astronomers most of all in the magnitudes encountered in the universe is the relation between the size of a star and that of an atom; millions of kilometres — that is the diameter of a star and

hundredth millionths of a centimetre—that is the diameter of an atom. This means that an atom is 10^{19} times less in size than a star (on the average). The mass of the Sun contains approximately 10^{56} atoms, and the fate of this star depends on the state and transformations of this enormous number of minute structures. Under the conditions prevailing in the interiors of stars, atoms manifest great activity; they not only lose their electrons (are ionized), but their nuclei enter into nuclear reactions. An atom consists of a nucleus carrying a charge of positive electricity, surrounded by electrons moving around it. The radius of the electron orbits is equal to about 10^{-8} cm¹. The size of the nucleus is much smaller and has a value of from 10^{-12} to 10^{-13} cm. Hence, the space between the nucleus and electrons is very great in comparison with the size of the nucleus. The atom is by no means a dense particle; most of the volume we have in mind when we speak of a radius of 10^{-8} cm is actually free of particles. The density of nuclear matter, on the contrary, is extremely high. The mass of an electron is so small that it can be entirely neglected in most cases; consequently, the nucleus constitutes practically all the mass of the atom. The small volume of the nucleus is occupied by particles compressed to a density of 10^{14} g/cm³. The nucleus is composed of protons (*p*) carrying a positive charge and having a mass equal to unity (to be more exact, 1.0072767) according to the carbon scale and neutrons (*n*), neutral particles of a mass of 1.0086654. According to all available data, the proton and neut-

¹ In atomic physics the unit usually employed for measuring distances is the angstrom, i.e., 10^{-8} cm. This unit is denoted as Å and approximately corresponds to the diameter of the hydrogen atom. At present, when measuring small distance, the unit often used is the nanometre (10^{-9} m):

$$1 \text{ Å} = 0.1 \text{ nm}$$

ron are two different states of one and the same particle known as a nucleon. The conversion of a proton to a neutron and *vice versa*, however, results in the appearance of new particles. If a neutron is converted to a proton, there simultaneously appears an electron, \bar{e} , and a very light particle called an anti-neutrino, $\tilde{\nu}$:

$$n \rightarrow p + \tilde{\nu} + \bar{e}$$

The energy released when a neutron is converted to a proton causes the emission of β -particles which are electrons moving with great velocities (up to 99 per cent of the velocity of light). It is apparent that when an atomic nucleus undergoes such a transformation, the number of positive charges in the nucleus increases. The number of positive charges, as is known, determines the atomic number of the element in Mendeleev's periodic system. Consequently, the resulting nucleus should have an atomic number that is greater by one than the atomic number of the initial nucleus.

The conversion of a proton to a neutron must be accompanied by the emission of a positive particle, otherwise the number of charges in the right-hand side of the equation will not be equal to those in the left-hand side. As a matter of fact, a positively charged particle of a mass equal to that of the electron, the positron e^+ , has been detected and studied.

The reaction of the transformation of a proton to a neutron is also accompanied by the appearance of a very light particle, the neutrino (a neutrino differs from an anti-neutrino in spin, i.e., in the direction of its rotation and certain other properties which we'll not go into here):

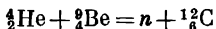
$$p \rightarrow n + e^+ + \nu$$

The resulting nucleus has an atomic number which is less by one than that of the initial nucleus. A chan-

ge in the atomic number signifies the conversion of one element into another — its neighbour in the periodic system. In other words, the initial and resulting substances in nuclear reactions are different elements. That is where nuclear reactions differ basically from ordinary chemical reactions in which transformation of molecules takes place but the conversion of elements is never observed.

2. PROPERTIES OF SOME ELEMENTARY PARTICLES

It was the study of the nuclear reactions of α -particles, i.e., helium nuclei, and beryllium nuclei that led to the discovery of neutrons. Let us denote the helium nucleus by the symbol ${}^4_2\text{He}$. The upper left numeral indicates the mass of the nucleus; the lower left numeral, the nuclear charge. The beryllium nucleus accordingly is denoted as ${}^9_4\text{Be}$. The reaction is expressed by the equation



As a result of the reaction a carbon nucleus and a neutron, n , are formed. The neutron is not deflected by an electric or magnetic field and does not ionize air; that is why it is hard to detect it. However, on colliding with a hydrogen nucleus, the neutron transmits energy to it and makes it move. The motion of the proton is easily detected because it is a charged particle. Therefore, neutrons are studied by directing them onto a compound containing hydrogen (water or paraffin). The appearance of protons indicates the presence of neutrons.

The discovery of the neutron was the basis for developing the proton-neutron structure of the atomic nucleus (W. Heisenberg, D. Ivanenko). It was assumed that the nucleus consists of protons and neutrons;

that the mass of the nucleus is equal to the sum of their masses and the atomic number is determined by the number of protons.

In the atomic nucleus the protons and neutrons are continuously being converted into each other at such a rate that in the normal state no emission of particles can be observed. In these transformations, however, the neutron in the nucleus is quite stable whereas the neutron emitted from the nucleus disintegrates rather energetically (its half-life is equal to 12 minutes). Soon after the discovery of the positron, another remarkable particle was discovered, whose existence was postulated, on the basis of theoretical reasoning, by Pauli back in 1933. This particle was called a neutrino. A characteristic property of the neutrino, which made it difficult to obtain evidence of its existence, is its unusual penetrating capacity. B. Pontecorvo made calculations which showed that a neutrino could penetrate unimpeded a cast-iron block of a thickness exceeding a billion times the distance from the Earth to the Sun. That is the reason why it is so difficult to investigate the neutrino. Only a nuclear reactor¹, which is a powerful source of these particles, proved to be suitable for the experiments carried out by Reines and Cohen. They proved that these particles really exist. The mass of a neutrino when at rest is equal to zero. The entire mass of a neutrino is associated with its motion, and it reacts with other particles very feebly. The mean free path of the neutrino is close to the diameter of the universe.

How is it that protons and neutrons are retained close to each other and form particles (atomic nuclei) with an incredibly high density of 10^{14} - 10^{15} g/cm³?

¹ At the present time, other processes are known that result in the appearance of neutrinos.

The reactive forces that bind the nuclear particles together are of a peculiar nature. In order to understand the reasons for their appearance let us consider the behaviour of an electron in an electric field. Electrons interact with photons. The electron continuously absorbs and emits photons. This process takes place so quickly that the energy of the system as a whole does not, in essence, change (otherwise when a photon is emitted by an electron, the total energy would increase; and when a photon is absorbed, decrease, because the photon itself possesses energy). Such processes are called *virtual* ones. The results of the virtual processes occurring when an electron reacts with the electric field cannot, in essence, be observed, and the law of conservation of energy is not violated because it applies to values that can be observed. On the other hand, if energy is supplied from an outside source, photons can be detected. Thus, an increase in the velocity of the electron causes radiation, i.e., photons are actually emitted. This conception was applied to nuclear forces. The role of the photon in the exchange processes in the nucleus is played by particles called π -mesons, the existence of which was predicted by Kh. Yukawa. Mesons were discovered in 1947, 12 years after Kh. Yukawa had predicted their existence.

Mesons (neutral and charged π -mesons) are virtually emitted and absorbed by nucleons and in this way bind them. Consequently, π -mesons, or pions, play a very important part in determining the nature of nuclear forces. Mesons are short-lived particles but in the nucleus they participate in such rapid processes that their life is long enough to carry out this binding function. The forces connected with virtual exchange by means of mesons are not the only ones that act in the nucleus; other kinds of forces are known as well as other types of elementary particles.

3. NUCLEAR REACTIONS

Nuclear reactions are caused by the interaction of an atomic nucleus with some elementary particle or with the nucleus of another, lighter atom. In the general case, under consideration are processes in which a target nucleus is subjected to bombarding by neutrons, protons, helium nuclei (α -particles) or even relatively heavy nuclei, for example, carbon nuclei. If the bombarding particle carries a positive charge, its interaction with the target nucleus is impeded because of the repulsive forces; of importance are also the centripetal forces that arise when impact is not head-on.

As a result, only high-energy particles can enter into a nuclear reaction. This is, in a measure, analogous to what is observed in ordinary chemical reactions; only nuclei or atoms with a certain excess energy, the energy of activation, are chemically active. In nuclear processes this excess for charged particles is very great: 15 million volts for the reaction involved in the formation of a deuteron from two protons. However, if the bombarding particle has no charge (a neutron), the chances of its reaction with the nucleus will be great even at low energies. In this case, an increase in velocity will have the opposite effect. Neutrons which move too quickly do not remain near the target nuclei long enough to react with it and the rate of the nuclear reaction diminishes. For this reason it was the reactions of various atomic nuclei with slow neutrons that made it possible to obtain much valuable information about nuclear reactions in general. Although charged particles are employed for bombarding target nuclei, in this case, special and very expensive apparatus is needed for accelerating the particles to such speeds that they burst through the energy barrier

of the target nucleus and make their way inside the nucleus.

A common feature of all nuclear reactions is the formation of a compound nucleus, i.e., a target nucleus that has absorbed a bombarding particle. The size of an atomic nucleus is small (10^{-12} - 10^{-13} cm) and a very short time (10^{-22} s) is needed for the particle to pass this infinitesimal distance. This is characteristic nuclear time. Actually, the particle reacts with the nucleus during a period of time which is tens and hundred millions of times longer; hence, the life time of a compound nucleus is equal to 10^{-16} - 10^{-15} s. In this short interval of time the energy imparted to the nucleus by the incoming particle is distributed among the nucleons present there. It is not very likely that the energy necessary for ejecting a particle from the nucleus will be concentrated on one nucleon; and consequently, for a short time the nucleus remains in a state of excess energy, i.e., in the excited state. In some cases the nucleus returns to the ground state, losing its excess energy in the form of quanta of γ -radiation. This type of reaction in which a nucleus holds an additional particle is called capture.

It does not matter how the nucleus came to be excited; therefore, the reactions incited by α -particles, protons and neutrons, in general, resemble one another, differing only in the energy required to overcome the repulsive forces, i.e., the Coulomb barrier.

4. NUCLEAR ENERGY SOURCES

The small size of atomic nuclei and the corresponding extremely high density of nuclear matter reaching 10^{14} g/cm³ imply that powerful forces compress the constituents of the nucleus and maintain the stability of the whole system of nucleons. Equilibrium in the

nucleus can, however, be disturbed sometimes because of external action such as the penetration of α -particles, neutrons and protons into the nucleus and sometimes due to internal processes of redistribution of energy, of which we know very little as yet.

As a result of the disturbance of equilibrium, the nucleus passes to the excited state; then the reconstruction of the nucleus, i.e., a nuclear reaction (nuclear conversion) follows. Instead of the original nucleus and the bombarding particle, another nucleus is produced, and often a different particle is emitted.

The most amazing thing in these reactions is that in the general case, the sum of the masses of the initial particles is not equal to the sum of the masses of the resulting particles. Profound analysis has shown that, virtually, in any chemical reaction accompanied by a change in energy of substances, the sums of the masses of the initial and resulting substances must differ from each other. This is because a change in energy E is equivalent to a change in mass E/c^2 (where c is the velocity of light) and, conversely, if the mass changes by a value m , this is equivalent to a change in energy equal to mc^2 (according to Einstein's famous equation for mass-energy equivalence).

Ordinary chemical reactions, however, are accompanied by extremely small changes in mass in the reacting and resulting substances, which cannot be detected by any methods of precise weighing; this is quite natural because the energy effects of such reactions are very small¹. It is quite another matter when nuclear processes are concerned. The first investigators of radioactive transformations were astonished by the enormous amount of energy released on decay of nuclei

¹ For example, the thermal effect of the reaction of the formation of 1 mole CO_2 (94 kcal) corresponds to a change in mass of only 4.39×10^{-9} g.

of natural radioactive substances (radium, polonium and others). The energy effects of nuclear reactions exceed those of ordinary chemical reactions millions of times, and it is easy to understand that, in this case, the change in mass of the substances that participate in the reaction can be observed. Thus, the conversion of four protons to the helium nucleus corresponds to a reduction in mass (mass defect) by 0.028 atomic mass unit (according to the carbon scale), which, in turn, corresponds to the release of an enormous amount of energy equal to 0.25×10^{20} erg:

$$E = (4 \times 1.008 - 4.004) c^2 = 0.028c^2 = 0.25 \times 10^{20}$$

- That is, 0.25×10^{20} erg/mole is obtained when 4 grams of hydrogen are converted to helium. Expressed in terms of calories this amounts to 6.4×10^8 kcal/mole; whereas in ordinary chemical reactions heat is evolved or absorbed in a quantity measured by hundreds (10^2) of kilogram-calories per mole of substance.

The mass defect is expressed either in atomic mass units (AMU) or as mc^2 where m is the mass of an electron (9.28×10^{-28} g). The mass of an electron is 1840 times less than an AMU; hence, $1840 mc^2$ corresponds to the energy released when the mass is decreased by 1 AMU. It follows, therefore, that for the reaction of formation of helium the energy released is equal to

$$E = 0.028 \times 1840mc^2 = 52mc^2$$

The unit mc^2 is equal to the kinetic energy of an electron moving through a potential difference of 510,000 V = 5.1×10^5 eV = 0.51 MeV (megaelectron-volt; M denotes a million; MeV, a million electron volts). Thus the above reaction gives an energy of $0.51 \times 52 = 26.52$ MeV. Frequently, the atomic energy unit (AEU) is employed. It is equal to the energy

corresponding to a change in mass by 1 AMU, and since 1 AMU is equal to 1.67×10^{-24} , the energy will be $1.67 \times 10^{-24} c^2$; 1 AMU will be

$$\frac{1.67 \times 10^{-24} c^2}{mc^2} \times 0.51 = 931 \text{ (MeV)}$$

The greater the energy released when the nucleus is formed from its constituents (protons and neutrons), the more stable the nucleus.

The formation of a deuteron, the nucleus of deuterium, from a proton and a neutron ($p + n = d$) corresponds to the change in mass that occurs as the result of the transformation of a proton (of mass 1.007596) and a neutron (of mass 1.008986) to a deuteron (of mass 2.014194):

$$1.007596 + 1.008986 - 2.014194 = 0.002388$$

This mass corresponds to a release of energy equal to 2.2 MeV. If another neutron is added to the deuteron, the nucleus of tritium (triton) is obtained; the energy that binds the second neutron is greater than the binding energy of the first neutron and is equal to 6.72 MeV. Triton is relatively stable. This nucleus disintegrates to form ${}^3_2\text{He}$ and an electron, releasing a small amount of energy (19.2×10^3 eV).

The binding energy of the nucleus is the amount of energy required for dissociating the nucleus into its constituents, protons and neutrons. The binding energy of the oxygen nucleus (${}^{16}\text{O}$) is as great as 128 MeV; of aluminium, 224 MeV; of chlorine, 298 MeV; of xenon, 1096 MeV. These values clearly illustrate the remarkable stability of the majority of nuclei. Stability depends on the number of nucleons. The most stable nuclei are those with a mass number from 40 to 100. The binding energy calculated per one nucleon dimi-

nishes from 8.7 MeV (in the most stable nuclei) to 7.5 MeV in uranium. Nuclei of small mass, as we have already seen from the examples given above, are less stable; in them the binding energy per one nucleon is as small as 1 MeV. Nuclei with even numbers of protons and neutrons (even-even nuclei) have binding energies of the highest values; even-odd nuclei are less stable and odd-odd nuclei are even less stable. This is due to the peculiar properties of the nuclear forces which act on the nucleons within the nucleus.

In nuclear reactions the excitation energy of a compound nucleus is also very great. Thus, for instance, when a neutron excites an atomic nucleus having a mass number of about 100, the energy in the nucleus is increased by 10 MeV. Consequently, the increase of energy of one nucleon in such a compound nucleus is approximately 0.1 MeV; this corresponds to a temperature of a billion degrees. The compound nucleus is heated to a temperature of a billion degrees! Comparing the nucleus with a drop of liquid, which it does resemble in some of its physical properties, it is sometimes said that the particles evaporate from such a heated nucleus.

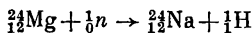
5. TYPES OF NUCLEAR REACTIONS

Let us consider the most important types of nuclear reactions¹.

¹ In those cases when atoms play the role of targets or are the end products resulting from nuclear reactions within the target, atomic nuclei are denoted by the following chemical symbols; H — protium, D — deuterium, T — tritium, He — helium, etc. The bombarding particles are denoted by the following letters: p — proton, d — deuteron, n — neutron, α — alpha-particles.

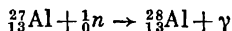
Reactions Induced by Neutrons

These reactions are of great importance in space chemistry. Neutrons readily penetrate into various nuclei, and charged particles can be emitted due to the disintegration of the resulting compound nucleus. This type of reaction is characteristic of nuclei of isotopes of small mass, for instance,



In elements with nuclei of a medium mass, partial inelastic scattering of neutrons occurs. This means that the nucleus which absorbs a neutron also emits a neutron (another one) and remains in an excited state; this is followed by the radiation of a γ -quantum and the transition to the normal state.

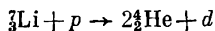
The capture of a neutron by a nucleus is also observed:



The aluminium nucleus resulting from this nuclear reaction, the same as the isotope ${}^{24}_{11}\text{Na}$, is radioactive; reactions induced by neutrons often result in the formation of unstable radioactive nuclei and therefore are important means of obtaining artificial radioactive elements which are widely used in science and technology for solving various complex problems.

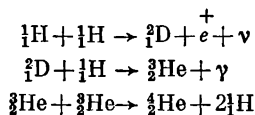
Reactions Induced by Protons

Reactions induced by protons include, for instance, the reaction of the conversion of lithium to helium:



This reaction is accompanied by a release of energy.

At very high temperatures, nuclear reactions develop in the interior of stars, as a result of which four protons are converted into the helium nucleus. One of these reactions is known as the proton cycle and proceeds according to the following scheme:

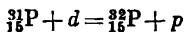


The formation of helium is a powerful source of energy that maintains the energy equilibrium in a star. Specifically, these reactions maintain the temperature of the Sun.

Reactions Induced by Deuterons

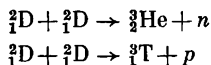
A deuteron consists of a neutron and a proton bound together rather feebly: the binding energy is 2.22 MeV. The low binding energy is due to the size of the deuteron which, on the average, exceeds the radius of action of nuclear forces.

When a deuteron approaches an atomic nucleus, the nuclear forces repel the proton but have no effect on the penetration of the neutron into the nucleus. As a result, the weak bond between the proton and neutron in the deuteron is broken, the neutron is absorbed by the nucleus and the proton is ejected. This explains the character of nuclear reactions in which deuterons participate, these reactions are often accompanied by the emission of a proton. The following processes are examples of such reactions:



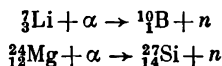
${}^6_3\text{Li} + d = {}^7_3\text{Li} + p$ (conversion of lithium isotope of small
mass to the heavy one)

By means of reactions induced by deuterons it became possible to obtain the ${}^3_2\text{He}$ isotope and to synthesize tritium:



Reactions Induced by α -Particles

Alpha-particles were one of the first means by which it became possible to penetrate into the nucleus and induce nuclear reactions. An especially important role in the development of atomic physics was played by the reaction of α -particles and beryllium nuclei because this reaction causes the emission of a neutron. Neutrons also appear when a stream of α -particles acts on the nuclei of lithium, magnesium and other elements:



Photonuclear Reactions

A nucleon can be torn out of an atomic nucleus by the action of a powerful γ -quantum on the nucleus. Only γ -quanta with an energy greater than 8 MeV can be used to bring about this process. With the aid of a betatron, synchrotron or other accelerators of electrons it was possible to investigate the reactions in which a neutron escapes from an atom (for example, from the copper atom) under the action of γ -quanta having an energy of about 20 MeV. Reactions in which neutrons and positrons were forced out of the atoms of indium, thorium and other elements were also studied.

One of the conclusions drawn from investigations in the field of photonuclear processes is that the γ -quan-

Table 9

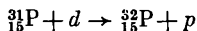
Some Typical Nuclear Reactions

Bombarding particle	Brief denotation of nuclear reaction				
p	${}^7_3\text{Li} (p, n) {}^7_4\text{Be}$	${}^{19}_9\text{F} (p, d) {}^{18}_8\text{O}$			
d	${}^9_4\text{Be} (d, n) {}^{10}_5\text{B}$	${}^{12}_6\text{C} (d, n) {}^{13}_7\text{N}$	${}^{14}_7\text{N} (d, p) {}^{15}_7\text{N}$		
n	${}^6_3\text{Li} (n, d) {}^3_1\text{T}$	${}^{12}_6\text{C} (n, \alpha) {}^9_4\text{Be}$	${}^{14}_7\text{N} (n, \alpha) {}^{11}_5\text{B}$	${}^{14}_7\text{N} (n, p) {}^{14}_6\text{C}$	${}^{14}_7\text{N} (n, 2\alpha) {}^3_3\text{Li}$
γ -quantum	${}^2_1\text{D} (\gamma, n) {}^1_1\text{H}$	${}^9_4\text{Be} (\gamma, n) {}^8_4\text{Be}$			

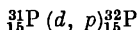
tum is not produced in these reactions but that energy is absorbed by a proton on the surface of the nucleus, i.e., a phenomenon analogous to the photoeffect occurs.

Brief Denotations of Nuclear Reactions

It is convenient to write down the equations of nuclear reactions in the following way: the initial nucleus is denoted by the usual chemical symbol; then, in parentheses, are written the symbol of the particle that acted on the nucleus and, after a comma, that of the particle or γ -quantum emitted in the reaction. To the right of the parenthesis is written the symbol of the resulting nucleus; for instance, the reaction



can be written as follows:



where d is a deuteron and p is a proton.

Table 9 gives some brief denotations of nuclear reactions.

6. SOURCES OF SOLAR ENERGY

From where does the Sun derive its energy? Due to what processes does it pour out streams of radiation, maintain the temperature of plasma at a level of tens of millions of degrees and continue this extravagant activity during many billions of years?

There is no ordinary chemical reaction that could supply the Sun with the necessary amount of energy! Even rough calculations show that such chemical reactions are unsuitable for furnishing the required energy. It was once supposed that the source of energy

could be processes of radioactive decay. But there is very little radium and, in general, small quantities of all heavy nuclei on the Sun. Evidently some other process provides the Sun with energy. It should be remembered that the Sun consists almost entirely of hydrogen and helium. Perhaps this is the clue to the mystery of its energy resources. Can hydrogen be transformed to helium? How much energy is evolved in this reaction? We have already calculated it. It was found that in the reaction $4\text{H} = \text{He}$, i.e., as a result of the conversion of four atoms of hydrogen to a helium atom, the total mass is reduced by 0.028 AMU and an enormous amount of energy equal to 26.5 MeV is released. It may be that the Sun is a gigantic plasma fire in which hydrogen burns and is consumed in the formation of helium. The energy thus obtained is quite sufficient to maintain a temperature of millions of degrees for billions of years.

Solar energy is dispersed in space and even reaches our planet. According to the law of mass-energy equivalence a certain amount of mass would be equivalent to a certain amount of energy if mass disappeared and energy appeared in its place. Hence, the loss in mass corresponding to solar radiation can be determined. The so-called mass defect resulting from nuclear reactions carried out in atomic reactors during several months amounts to grams, but in nuclear processes on the Sun it amounts to millions of tons. Every second the Sun loses an energy of 10^{23} kcal or 4.182×10^{33} erg: the mass which corresponds to this energy can be found from the equation $E = \Delta mc^2$:

$$\Delta m = \frac{E}{c^2} = \frac{4.182 \times 10^{33}}{9 \times 10^{20}} = 46 \times 10^{11} \text{ g or } 4.6 \times 10^6 \text{ tons}$$

Every second the Sun loses more than 4.5 million tons of mass and as a result of this process produces

powerful streams of radiation. Only about 2 kg of mass comes every second to our Earth, the little blue planet, and this amount supplies the energy for all life on Earth!

Cyclic Nuclear Processes on the Sun

Thus it seems that the source of energy has been found. Not only the Sun, but many stars much larger than the Sun (the very luminous white and red giants) are hydrogen-helium spheres in which hydrogen is being converted to helium. Our universe is a world of hydrogen and helium. At once there arise several questions: is it so easy to combine four hydrogen nuclei, i.e., four protons, to form one particle, if we take into account that the chances that four particles repelling each other will meet at one point must be very small? Why, in general, are only two elements considered when all the elements (although in small quantities) are present in outer space? The Sun, for example, contains over 60 elements; many elements are found in stars, comets and interstellar matter. Where did they come from and what part do they play in nuclear reactions? We'll, first of all, answer the first question. It is in fact difficult to unite four particles all at once, but it is easier to first unite two of them and then the other two. Evidently, two protons combine with one another to form a nucleus of heavy hydrogen, the deuterium. In this reaction a particle of small mass, the positron, and the mysterious neutrino appear. Then the heavy hydrogen nucleus reacts with a proton to form the helium nucleus with a mass of 3 and a γ -photon (radiation). Finally, two particles, nuclei of the helium isotope, ${}^3_2\text{He}$, collide to form the end product ${}^4_2\text{He}$ and two protons. These protons enter into

the reaction again. On examining the schematic representation of this reaction given on the diagram in Fig. 21, it can be noticed that it is similar to a diagram illustrating the action of a catalyzer: a number of protons enter into the reaction

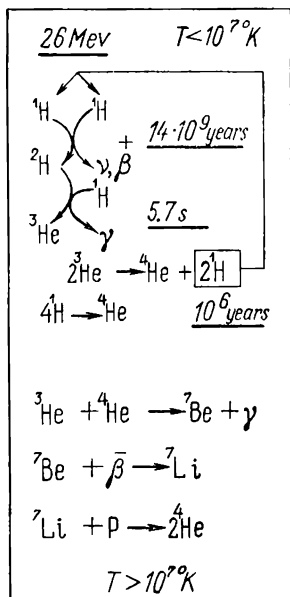


Fig. 21. Diagram of proton cycle

and leave it, involving additional protons in the process. The temperature at which this process takes place is $10^7 \text{ }^\circ\text{K}$ (K denotes Kelvin degrees; the temperature is reckoned from absolute zero equal to -273°C). If the temperature exceeds $1.3 \times 10^7 \text{ }^\circ\text{K}$, another reaction begins to proceed — branching of the proton cycle. The nucleus of the atom 3He reacts with the 4He nucleus to form the beryllium nucleus which captures an electron and is transformed to a lithium nucleus, and the lithium nucleus, on absorbing a proton, forms 4He (Fig. 21). The energy effect is slightly smaller — 25.6 MeV. The energy of this proton cycle is the basis of the energy

balance in the Sun. The catalytic character of nuclear processes is even more markedly expressed in another cycle which occurs at very high temperatures.

This cycle is called the nitrogen-carbon cycle because in it the nuclei of nitrogen and carbon atoms play the part of catalyzers which facilitate the reaction of

transformation of hydrogen to helium. The diagram of the nitrogen-carbon cycle is shown in Fig. 22.

As can be seen, the nuclei of nitrogen isotopes of masses 13, 14 and 15, the isotopes of oxygen of nuclear mass 15 and isotopes of carbon of nuclear masses 12 and 13 take part in this cycle. During the work of

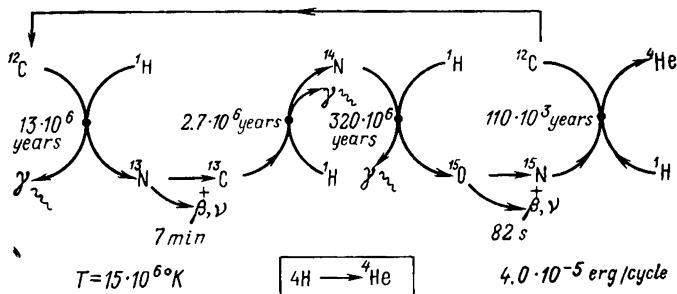


Fig. 22. Diagram of nitrogen-carbon cycle

this cycle positrons, neutrinos and γ -quanta, i.e., short-wave radiation, are formed. The cycle functions at a rate which would seem to be altogether inconceivable on an Earth scale. A hydrogen nucleus entering the cycle has a chance to come out of it as a helium nucleus in 50 million years! Not too quickly, it appears. There is so much hydrogen in the Sun, however, that even at this rate the work of the cycle is quite satisfactory and the cycle plays an important role in providing the Sun with energy.

At temperatures of 10^8 - 10^9 K , other cyclic nuclear reactions occur, which also play a part in supplying the stars with energy. Such is the neon-sodium cycle in which the isotope of neon and sodium take part as shown in Fig. 23. The result is the same: the conversion of hydrogen to helium is accelerated. Can helium be

considered to be the final product which does not undergo any further change, i.e., something like ash in the nuclear furnace?

Helium is not the final product of nuclear reactions. On the contrary, the processes in which helium nuclei

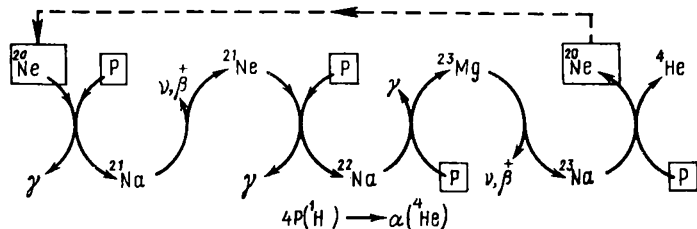


Fig. 23. Diagram of neon-sodium cycle

are involved initiate the synthesis of heavier nuclei. At temperatures of 10^8 - 10^9 °K, the synthesis of various elements takes place in the stars, and the different stages in this synthesis determine the general physical state of a star. Thus, it appears that in the magnificent stellar laboratories, from hydrogen nature produces all the elements known on the Earth.

Evolution of Stars and Synthesis of Elements

1. STAGES IN THE LIFE HISTORY OF STARS

Thus, the stars twinkling in the sky are extremely hot gaseous spheres or dense masses of matter wherein violent reactions continually produce complex atomic nuclei from plasma. Consequently, the life of a star and that of the atom are closely related.

The problems involved in the theory of stellar evolution cannot be considered to be solved; there are many riddles of a chemical and physical nature that still await their solution. The general conception of a star's life would perhaps be even vaguer if astronomers had not been able to observe stars at different moments in their development. It was an easier matter to determine the sequence of the stages observed because the laws of atomic physics as well as the laws of chemistry are the same for all parts of the universe, and certain states of stellar matter (e.g., the plasma state) can be simulated in laboratories on the Earth.

It is quite probable that the initial state of stellar matter was a cloud of gas and dust. The main components of the cloud were hydrogen and helium. The mutual gravitational attraction of the enormous number of particles (atoms and ions) results finally in the appearance of forces that condense the gaseous sphere. As the particles approach each other, there appears

another force that hinders the limitless condensation of matter: this force is gas pressure.

Since the gravitational forces and the forces of gas pressure are equal, the gaseous sphere (the prevalent star type) is in a state of equilibrium. Approximate calculation shows, for instance, that in the centre of such a star as the Sun the gas pressure should reach about 10^{10} atmospheres. Hence, since the average density of a star is equal to that of substances on the Earth, the temperature in the centre of the Sun must attain millions of degrees. According to available data, the temperature in the interior regions of the Sun is equal to 15 million degrees. Under such conditions all the atoms are completely ionized. Calculation of the temperature of a gas requires at least an approximate knowledge of its molecular mass. For a mixture of different particles it is enough to know the average molecular mass.

It is known that for atoms that are not too heavy the atomic number Z (i.e., the number of electrons in the atom, equal to the number of positive charges in the nucleus) is equal to about half the mass number: $Z = m/2$. If the total number of electrons is denoted as n_e and the atomic mass as m , then, when ionization is complete, there will be $n_e + 1$ particles (one nucleus and n_e electrons).

The average mass of a particle will be equal to $m_{av} = \frac{m}{n_e + 1}$ and since $m = 2Z = 2n_e$, then $m_{av} = \frac{2n_e}{n_e + 1} = \frac{2}{1 + 1/n_e}$

Hence, the average molecular mass of stellar matter is equal to approximately two or less. If the star contained only hydrogen for which $Z = m = n_e = 1$, the average molecular mass of its matter would equal 0.5.

The results of these calculations would be erroneous if the content of heavy atoms in stars were considerable. But, apparently, it does not exceed 4 per cent and is usually even less. Therefore, it is permissible to take the average mass of stellar matter.

Calculations based on these reasonings show that the temperature in the centre of hot luminous stars (for example, some of the stars in the constellation of Orion) equals $54,000,000^{\circ}\text{C}$; for cooler stars (Vega), the temperature is equal to $18,000,000^{\circ}\text{C}$; for Procyon it is "only" $8,000,000^{\circ}\text{C}$.

Because of the high temperature in the centre of stars, energy is transferred from the central regions to outlying ones by radiation, convection or conduction, depending on the state of the star. The transfer of energy to the outer regions of hot stars determines their luminosity. Since radiation is responsible for the transfer of energy in this case, the luminosity of a star depends on its size; larger stars are more luminous because they have a larger surface to radiate light.

The process of the condensation of interstellar matter and formation of the nuclei of stars occur continually. In our days, in the far-distant nebulae, for instance, in the famous Andromeda Nebula, stars are still appearing. Opaque gaseous bodies (nuclei) can be observed on photographs of the Horsehead Nebula (Fig. 24).

Let us follow the further development of star formation. Due to gravitational forces, the degree of condensation and the temperature gradually increase. While the temperature remains within the limit of a thousand degrees, the reactions that take place are ordinary chemical processes, the most important of which are the reduction of metals, decomposition and evaporation of unstable compounds, the formation of radicals, etc. If the conglomerate mass is great, the

increasing compression of the dense sphere results in such an intense evolution of heat that nuclear reactions begin to occur. What nuclei participate in these reactions?

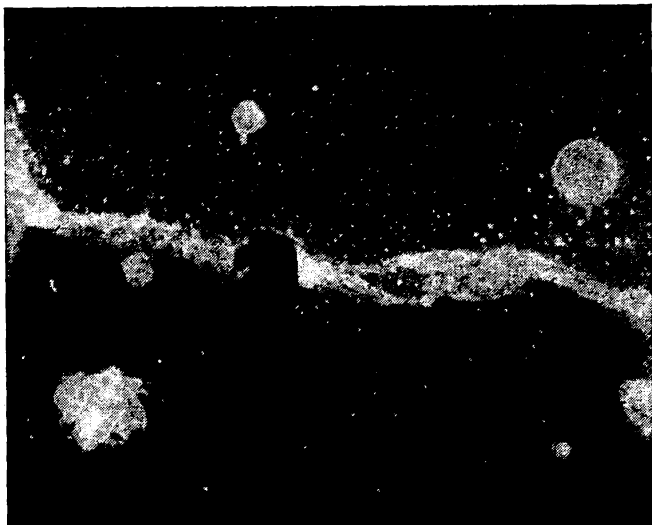


Fig. 24. The Horshead Nebula in the constellation Orion. Emission of hydrogen, helium, nitrogen, carbon, oxygen is excited by a superhot star in the vicinity of the nebula

In general, the rate of occurrence of elements decreases with increasing atomic number. Heavy elements occur more rarely than light ones do. After the ascent of the curve of occurrence of elements near iron (the iron peak), there follows a descent and there are relatively few nuclei with numbers exceeding 50. What nuclei are most frequently found in outer space? The

most abundant element could be the raw material from which other elements were formed.

Hydrogen is the most widespread element in outer space! It is this element that is found in the interstellar medium, in the hot masses of gas of the giant stars; it constitutes $3/4$ of our Sun; it is the emission of hydrogen that is always detected in the spectra of far-distant nebulae. Helium is also very widespread. It should be observed that these two elements always accompany each other. If, as stated above, $3/4$ of the Sun's mass is made up of hydrogen, almost $1/4$ of it is made up of helium. Helium lines accompany hydrogen lines in the spectra of stellar atmospheres. The significance of the connection existing between hydrogen and helium was understood only after the nature of the transformations occurring in the magnificent laboratories of outer space was ascertained. The most important reaction that takes place in stellar interiors is the formation of helium from hydrogen; i.e., the reaction described when considering the source of solar energy.

As soon as the internal processes begin to proceed violently, the stellar matter increases in volume. The star, on expanding to a gigantic size, is naturally cooled down, and the temperature of its outer layers is reduced to the relatively low value of $3000-4000^{\circ}\text{K}$. The star appears in the area of the red giants (in the upper right-hand corner of the HR diagram). Whether the star will become a supergiant or a subgiant depends on its mass (a mass equal to 10-15 times the mass of the Sun is required for transformation to a supergiant).

Having lost a large amount of matter flung out into outer space by the whirlwinds and storms of the nuclear processes, the star after using up all its hydrogen begins to consume its helium. A great number of

nuclei of new elements are produced in the star's interior. Moreover, the star having decreased its mass and luminosity, gradually approaches the main sequence, moving downwards on the Hertzsprung-Russel diagram.

On the way to its place in the main sequence, the star can lose its gas envelope and other changes may occur, especially in large stars (many times larger than the Sun). Generally, the star moves slowly along the main sequence during billions of years. How does the life of a star end? It can be transformed into a small faintly luminous yellow dwarf; this corresponds to a downward shift to the right along the main sequence. Another end is also possible.

In some cases a process of expansion of the outer parts of the star begins: the star ejects into space enormous amounts of gas, in which the conversion of hydrogen to helium continues taking place, and the remnant of the star contracts. If the mass of the star is less than that of the Sun (about 1.2 times), under certain conditions contraction results in the formation of a white dwarf — a very small but extremely dense star. The size of dwarfs, on a stellar scale, is very small: a number of them have a diameter of only 8000 km (less than the diameter of the Earth), but the density of a white dwarf reaches 10^{10} g/cm³.

The compression of matter, as is known, is caused by gravitational forces and, therefore, the greater the mass of the star, the higher the effect of compression. If the mass of a star exceeds the mass of the Sun 1.2 times, the internal pressure in it (electron-gas pressure and radiation pressure) will no longer be able to balance the gravitational forces, and the star will begin to contract rapidly; this results in a so-called gravitational collapse. A collapse ends in a violent explosion, and the stellar matter is scattered over large areas of outer space.

A collapse may not occur; if the mass of the star lies in the range of 1.2 to 2 times the Sun's mass, another end is likely to occur. The stellar matter passes over to the neutron state: with very great degrees of compression electrons and protons can unite to form neutral particles, neutrons. As a result of the conversion to the neutron state, the density increases to even a greater extent and reaches values of the order of 10^{15} g/cm³. It is indeed rather difficult to conceive a density at which 1 million tons of matter is contained in 1 mm³!

A neutron star can also appear after an explosion, i.e., after a collapse causes the violent development of nuclear reactions and the scattering of matter. The "nut" remaining in the centre of the exploded mass is not only very hard but also very small — the diameter of a neutron star is only a few hundred kilometres or even a few tens of kilometres (Fig. 25).

The explosion and intense radiation that accompanies it are perceived as the appearance of a supernova. Such an explosion occurred in 1054: the Crab Nebula presents the imposing picture of the widespread expansion of the explosion products in outer space.

Neutron stars have magnetic fields (very strong ones). The matter in these stars is not motionless; it vibrates radially and otherwise; besides, the star itself revolves as a single body. As a result, neutron stars are sources of very intense and periodic radio emission. At the present time, the radiation of these so-called pulsating stars is being studied extensively.

In the Crab Nebula there is the pulsating star denoted as P 0532¹ which was formed as the result of the

¹ Pulsating stars are usually denoted as proposed by English astronomers: the first letter indicates the place it was discovered, the letter "P" indicates pulsating, the number indicates the time of direct ascent. Accordingly, the first pulsating

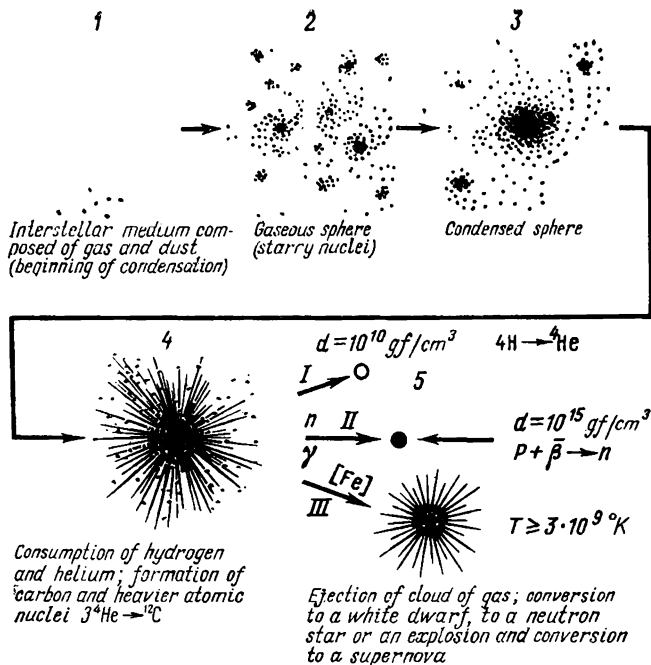


Fig. 25. Schematic representation of the evolution of stars:
 I — $m < m_S$ (1.2 times); II — $1.2m_S < m < 2m_S$ III — $m > m_S$
 (more than 2 times)

explosion of a supernova. There can, of course, be other reasons for the appearance of pulsating stars².

star was denoted as CP 1919: "C" indicates that Cambridge was the place it was discovered; 1919, the direct ascent equal to 19 h 19 min.

² The CP 1919 pulsating star is not a powerful source of radio emission as was previously supposed (the source is much farther from us than the pulsating star) and it originated from an unstable star (according to Goss and Schwartz).

As a result of a collapse, sometimes such dense stars appear that even radiation is not able to overcome their gravitational field. Such a star, consequently, cannot be seen; its existence is detected only by the effect it has on its neighbours. These superdense stars, bottomless gravitational drains, absorb energy and matter. They are called dark "holes". According to U. Press they do not retain a spherical form and they pulsate, being the source of gravitational radiation. The pulsating star Swan 10-1 emits X-rays, the period of pulsation being 0.1-10 s. Swan 10-1 is considered to be a binary star: a dark "hole" revolves around a giant star which is at a distance of 6000 light-years from the Earth. Like in the case of the Crab Nebula, it is a very powerful source of radiation. The invisible star probably has a mass equal to 2.5 solar masses and causes tidal waves in the giant star, gradually drawing off its atmosphere. It is possible that variation in the intensity of X-ray emission is associated with this phenomenon.

In the constellation Hercules an X-ray pulsating star with a period of 1.247 s has been discovered. By now 116 sources of X-ray emission have been registered: 75 of them are at the equator of the Earth's galaxy and 10 are beyond it (specifically, in the constellation Andromeda). There are also scattered sources of radiation in the constellation Coma Berenices.

The more complicated the nuclear reactions, the more difficult it is to study them theoretically and the harder it is to simulate them in laboratories on the Earth. At the present time, certain nuclear processes can be carried out in nuclear reactors and powerful cyclotrons; in the near future attempts to obtain stable plasma and to control the thermonuclear conversion of hydrogen to helium will be made. The synthesis of many heavy nuclei, however, is yet

unattainable, and this aspect of space nuclear chemistry still remains a field of conjectures and hypotheses.

It is supposed that it is during the explosion, in the process of the origination of supernovae (at temperatures of the order of 3×10^9 °K), that there appears a mixture of nuclei, protons and neutrons from which subsequently the nuclei of iron and other heavy elements are formed¹. Hence, the chemical reactions by which iron is formed in space differ considerably from those in which lighter elements are formed: iron atoms are forged in extremely hot furnaces and are produced as the result of violent processes the effect of which extends to a great distance from the site of the explosion (several light-years).

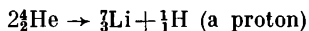
It should be noted that the development of nuclear processes in the period of collapse is characterized by diverse neutron capture and results in the appearance of nuclei of a dissimilar nature. But, by far, not all nuclei can be obtained by means of such transformations. The formation of certain elements cannot be explained by the work of neutron "furnaces" and other hypotheses had to be worked out to explain their appearance.

The origin of unstable nuclei such as the light nuclei of lithium, deuterium, boron, beryllium, which are rapidly absorbed in the nuclear reactions is also puzzling. Nevertheless, there is evidence, for instance, that the deep-red stars contain a large amount of lithium and in one of the blue stars an excess of the helium isotope ^3_2He has even been found. Where do these unstable nuclei come from? It has been assumed that in outer space, along with "hot" synthesis of

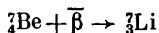
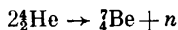
¹ At the time of an explosion of a supernova matter containing heavy elements is ejected into outer space. New stars are formed from this material and that is the reason why the content of heavy elements is high in young stars.

elements, resulting from neutron reactions, there also occurs "cold" synthesis. The masses of plasma produced, for example, as a consequence of an explosion in some galactic system are very unstable. Electromagnetic fields act in them, accelerating the motion of particles the same as in cyclotrons in laboratories on the Earth. The particles (protons, electrons, positrons, atomic nuclei) accelerated by vigorous gas streams to high velocities already begin to pick up speed under the effect of the electromagnetic fields, and on colliding, enter into reactions with each other. Under these conditions nuclei of new atoms are produced not as the result of thermonuclear processes but at much lower temperatures. Therefore, the formation of less stable nuclei and the synthesis of nuclei of heavy elements are possible.

According to D. Frank-Kamenetsky, the formation of odd isotopes of lithium and boron is explained by plasmic acceleration. The fact is that lithium with a mass number of 7 and boron with a mass number of 11 occur on the Earth and in meteorites in larger amounts than the even isotopes having a mass number equal to 6 and 10, respectively; this fact is of interest because, as has been stated above, usually it is even isotopes that are found more often. According to D. Frank-Kamenetsky, lithium-7 is obtained by the reaction



If a neutron is emitted, at first beryllium-7 is formed and then lithium-7:



The carbon nucleus, on reacting with a proton, can produce boron-11.

The atmosphere of young stars, as shown by spectral analysis, contains more lithium than the atmosphere of old stars: lithium produced in the plasmic streams is gradually burned up in the flames of thermonuclear processes.

2. THE MOST IMPORTANT NUCLEAR REACTIONS IN STARS

In the nuclear reactions proceeding in the interiors of stars, an active part is played by protons, helium nuclei (α -particles), and especially, by neutrons. The initial substance for the synthesis of all elements is hydrogen. In the equations for nuclear reactions, strictly speaking, it is not elements in the usual sense of the word nor atoms of simple substances that are involved, but the nuclei of atoms. At temperatures of millions and even billions of degrees only completely ionized atoms can exist, and ordinary ions, atoms and the simplest molecules are found only on the surface of stars (including that of the Sun).

The first stage in the synthesis of elements consists in the formation of helium from hydrogen. This reaction proceeding in the proton cycle, as is known, is one of the most important sources of stellar energy. Subsequently, a carbon nucleus can be formed from three helium nuclei. The reverse reaction was carried out in Earth conditions: the carbon nucleus was broken up into three particles. The same reaction can proceed in a different way: first the very unstable ${}^8_4\text{Be}$ nucleus is formed from two helium nuclei and then it reacts with another helium nucleus to give the ${}^{12}_6\text{C}$ nucleus and a γ -quantum. The first stage of this reaction is accompanied by the absorption of energy (95 keV)¹

¹ KeV is the symbol for a kiloelectronvolt equal to 10^3 eV.

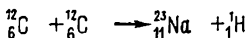
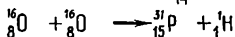
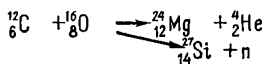
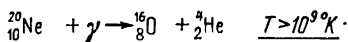
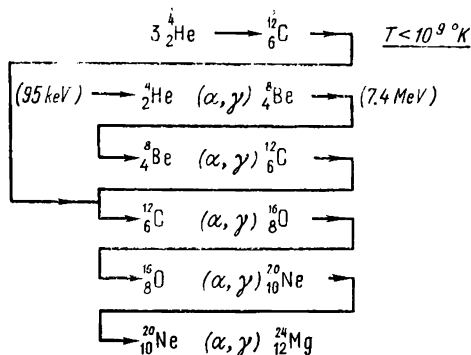


Fig. 26. Principal ways of nuclear synthesis of elements in stars

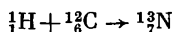
and the second stage, by the release of a comparatively very high energy of 7.4 MeV.

When the carbon nuclei react with α -particles, oxygen, neon and magnesium nuclei appear, as shown in Fig. 26.

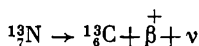
As the helium nuclei are used up, the extent of compression is increased and the temperature raised to billions of degrees, there begin reactions that break down the nuclei of carbon, neon and oxygen. These processes result in the formation of magnesium, neon, sodium, phosphorus, silicon and other elements (Fig. 26).

A very important part in the synthesis of elements is played by reactions induced by neutrons. Neutrons appear in stars mainly due to reactions taking place between α -particles and nuclei which contain a multiple number of α -particles plus one neutron. Thus, for example, the isotope ${}^9_4\text{Be}$ has a nucleus which can formally be regarded as consisting of two α -particles and one neutron; when an α -particle acts on this nucleus, ${}^{12}_6\text{C}$ and a neutron are obtained (it was the investigation of this reaction that resulted in the discovery of the neutron).

A proton reacts with the ${}^{12}_6\text{C}$ nucleus to form the nitrogen nucleus:

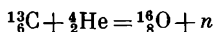


This isotope is unstable and is very quickly transformed to ${}^{13}_6\text{C}$:

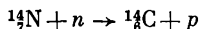


Both of these reactions are already familiar to us; the nitrogen-carbon cycle begins with them.

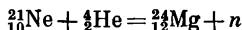
But if the ${}^{13}_6\text{C}$ nucleus enters into a reaction with α -particles, oxygen and a neutron will be obtained:



This reaction plays an important role in providing a star with neutrons. Part of the neutrons, undoubtedly, are quickly absorbed by nitrogen nuclei:



But besides the above source of neutrons there is another source which uses neon, ${}^{21}_{10}\text{Ne}$, as the initial material:



This neon isotope, in its turn, is formed in the neon cycle from ${}^{23}_{11}\text{Na}$ and a proton through ${}^{20}_{10}\text{Ne}$ and ${}^{21}_{11}\text{Na}$;

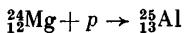
sodium, $^{23}_{11}\text{Na}$, as has already been stated, is formed when two carbon nuclei collide. In this way, the extremely hot interiors of stars are the site of the synthesis of quite a number of elements and the place where neutrons appear which give rise to further nuclear reactions.

Neutrons, of course, are more readily absorbed by nuclei than any other particles because they do not carry a charge and need not overcome any repulsive forces from the nucleus.

Reactions with neutrons of the (n, γ) type produce numerous new nuclei. Uniting successively with the nuclei of magnesium, calcium, sulphur, etc., neutrons form increasingly heavier nuclei. In order that the proper proportions of protons and neutrons be retained in the resulting nuclei, after the absorption of one neutron and before the absorption of the next neutron, a nucleus must emit an electron, that is, undergo γ -decay.

There are, however, certain peculiarities that limit the possibilities of the synthesis of heavy elements by (n, γ) reactions occurring in such stars as the red giants. First of all, with gradual addition of neutrons, astatine and francium are produced. These elements do not form any stable isotopes; their nuclei, on emitting α -particles, are converted to isotopes of lead and bismuth, and that is where the synthesis of nuclei ends. Secondly, heavy and light isotopes of elements are known which do not appear at all in the sequence of slow reactions of the (n, γ) type and are not produced in such processes.

At very high temperatures, reactions with protons are possible. Thus, magnesium can be converted to aluminium:



These processes, however, cannot explain all of the great variety of reactions of nuclear synthesis that actually occur. There has also arisen the problem associated with the relative abundance of elements of the iron group.

3. INTERSTELLAR MATTER

Up to now we have been talking about the composition of stars, planets, comets, meteorites, i.e., of celestial bodies. But they occupy only a tiny portion of space. What can be detected by chemical analysis in the boundless interstellar space? Can it be assumed that there is nothing but vacuum between the celestial bodies? Facts indicate that interstellar space is "populated"—there are atoms and ions of various elements and groups of atoms with unpaired electrons, i.e., radicals in it. Even molecules, and rather complex ones (for example, formaldehyde molecules!), can be found in outer space, far from celestial bodies. There is evidence of the presence of the radicals CN, CH, CH⁺, OH, CS and the molecules H₂O, CO, CoS, SiO, HCN, CH₃CN, CH₃OH, HCOOH and others¹.

One of the first ions to be detected in interstellar gas was the calcium ion. Since the calcium ion is also present in the surface gases of stars, it was rather difficult, by means of spectral data, to distinguish the radiation of calcium associated with a star from the radiation of interstellar calcium. When this was accomplished, however, it was found that interstellar space was literally filled in with calcium ions. The distribution of calcium ions is not altogether uniform. There

¹ Formamide molecules, HCONH₂, have been detected in the direction of the cloud Archer B2 and, probably, Archer A; this is the first interstellar compound containing H, C, O, N in one molecule.

are vast areas in outer space, clouds actually, where the content of calcium is very high.

It is relatively easy to detect calcium by spectroscopic analysis; it is harder to discover the presence of other elements in this way, and that is why evidence of their existence in the interstellar medium was obtained later. But, of course, the calcium ion is not there all alone. In outer space there are scattered far and wide, hydrogen atoms, ions of sodium, oxygen, titanium, potassium atoms CH and C radicals and other particles. The most abundant element (as concerns distribution and concentration) is hydrogen; of all matter contained in the interstellar medium, the percentage of hydrogen in it is the highest.

The concentration of matter, however, is inconceivably small. In the most perfect vacuum attained on the Earth the density of matter is greater than that in

Table 10

Density of Interstellar Gas

Substance	Density, g/cm ³	Substance	Density, g/cm ³
Hydrogen	2.7×10^{-24}	Calcium	7×10^{-28}
Oxygen	2.3×10^{-26}	Titanium	8×10^{-30}
Sodium	4×10^{-27}	CH	2×10^{-29}
Potassium	7×10^{-28}	C	1.5×10^{-29}

interstellar gas. Table 10 gives the density of substances in interstellar gas (according to B. Vorontsov-Velyaminov)¹.

¹ Interstellar space contains not only atoms, ions and radicals, but also dust, i.e., relatively large particles. B. Vorontsov-Velyaminov believes that the total mass of dust is, however, smaller than that of interstellar gases.

4. POSSIBILITY OF FORMATION OF ORGANIC COMPOUNDS DUE TO ACTION OF PROTONS IN SOLAR AND COSMIC RADIATION

The formation of organic compounds in outer space is, apparently, associated with processes in which protons participate.

The Sun is the main source of protons in outer space. Solar protons are subdivided into two groups: protons of the solar wind, with an energy of several kiloelectronvolts (flow of $10^{16} \frac{1}{\text{cm}^2 \cdot \text{year}}$) and protons of solar flares of a higher energy exceeding 0.5 MeV. Especially high-energy protons coming from some sources beyond the solar system but within the Earth's galaxy have an energy of 1 HeV (10^9 eV). The flow rate of these protons is low, only $10^8 \frac{1}{\text{cm}^2 \cdot \text{year}}$. They participate in nuclear reactions rather than in ordinary chemical reactions. Generating neutrons, they produce secondary protons (up to ten for every initial proton), and the secondary protons, on losing their energy, can enter into ordinary chemical reactions¹.

The collision of protons and carbon atoms can result in the synthesis of various hydrocarbons. Minute particles of silicates, oxides, carbonates, on reacting with protons, become the source of hydroxyl groups, thus making further development of synthesis possible. Of great interest are simulated experiments which were carried out with diamond crystals exposed to the emission of protons, deuterons and α -particles sped

¹ The effect of galactic protons, on the whole, is so feeble that a meteorite with a diameter of 2 m could accumulate through the action of these protons only a few thousandths of a per cent by mass of hydrogen in 4 billion years.

up in a Van-der-Graaf accelerator to an energy of 1.8 MeV. The target was cooled by means of liquefied nitrogen. It was found that CH , CH_2 , CH_3 radicals and hydrocarbon molecules were formed. The experiments also confirmed the assumption that hydroxyl groups were produced on the surface of silicate particles; this proceeds very slowly and results in hydration of the surface.

5. CHEMISTRY AND COSMOLOGY

Cosmology is the branch of astronomy that deals with the theories of the origin and evolution of the universe. It is quite natural that one of the central problems of this science is the question of how hydrogen appeared in outer space. This element, which in relation to others is the parent substance, was apparently formed as the result of an astonishing process. It is assumed by modern cosmology that several billions of years ago all matter in the universe was compressed to a very great degree, and in this state it contained neutrons stable under high compression. It is supposed that the temperature of this incredibly dense matter was very high. When the process of expansion began, the neutrons lost their stability and began to disintegrate to form protons, electrons and anti-neutrons. Protons were scattered in outer space and that was how hydrogen appeared.

If the temperature had been low, it would be more probable that a neutron combined with a proton to form deuterium nucleus. But there is very little deuterium in space and, consequently, there are more grounds for assuming the existence of hot primary neutrons. The most striking evidence obtained was the discovery in 1965 of remnants of heat radiation which accompanied the hot neutrons. This relict radiation does actually

fill up all space and reminds us of the violent events associated with the birth of hydrogen¹.

However, the problem of the origin of primary matter in the universe, neutrons or hydrogen, still remains unsolved. A group of English astronomers (Bondi, Gold, Hoyle) have even claimed that hydrogen atoms are continuously, although very slowly, created "from nothing"; another hypothesis assumes that primary matter was formed due to the energy generated by the expanding universe.

As yet there are no theoretical and experimental means of solving these colossal problems, although, in principle, they do not seem to be unsolvable.

Progress in atomic physics and nuclear chemistry has greatly influenced the cosmological theory, and one of the most striking examples of this influence is the introduction of the idea of antimatter and its properties.

The concept of antimatter developed gradually. At first physicists only knew about the very light negative particles, electrons, and the heavy positively-charged nuclei containing protons. Then very light particles having a positive charge were discovered; they were called positrons. A positron in relation to an electron is an anti-particle.

Progress in the field of theoretical physics of elementary particles and experimental data have also indicated the existence of anti-particles in relations to protons (anti-protons), in relation to mesons. i.e., particles having a number of masses between that of the electron and proton (anti-mesons) and even in rela-

¹ Recently, the presence of relict radiation of a temperature of 2.7°K was verified. The spectrum of the background infrared radiation studied with the aid of a rocket (on the Hawaiian islands) and the spectrum of an absolutely black body at a temperature of 2.7°K (wavelength 0.8-6 mm) are identical.

tion to the hardly perceptible neutrino (anti-neutrino). All information about the world of elementary particles appears to clearly indicate the possibility of the formation of an atom in which, instead of a positive nucleus, there would be a negative particle and, instead of an electron, a positive particle (positron). Consequently, in addition to ordinary hydrogen atom consisting of a proton (the nucleus) and an electron, there could exist an atom of anti-hydrogen in which a positron revolves around a nucleus (anti-proton).

What would happen if an atom collided with an anti-atom and the particles got a chance to react with each other? It is well known that the reaction of an electron and positron produces two γ -ray photons, and that the collision of a proton and anti-proton produces intermediate particles, mesons and anti-mesons, which in turn give electrons, positrons, then γ -quanta and streams of neutrinos and anti-neutrinos. In all these processes Einstein's mass-energy equivalence is observed, i.e., if a mass equal to m disappears, an energy equal to mc^2 appears in its place. For this reason, the reaction between atoms and anti-atoms must proceed in the form of a violent explosion. The reaction must be accompanied by the release of a vast amount of energy.

Nothing hinders us from assuming that, together with our galactic system, somewhere in outer space there exists another world, other galactic systems entirely made up of anti-matter. The chances of formation of usual atoms or those in which everything is "just the opposite" are equal. Why shouldn't a mysterious anti-world exist in the depths of outer space? Contact between such a world and ours would be equally dangerous for the inhabitants of both worlds: we would all instantly be converted to streams of photons, i.e., γ -quanta!

Is all this actually possible? Is there any proof that this reasoning goes beyond the limits of scientific fantasy which can neither be confirmed nor denied? Anti-matter does actually exist. Recently, Soviet scientists obtained anti-helium and studied its properties. Hence, there is nothing unusual in the development of cosmological theories based on the assumption that anti-matter participated in the creation of the universe.

S. Alfven and O. Klein have developed the concept of the origin of the universe from a dispersed cloud of matter in which atoms and anti-atoms were distributed evenly. The average distance between them in those far-distant times was so great that collisions occurred very rarely and had no catastrophic consequences. Gravitational forces gradually compressed the primary cloud, increasing its density. When the diameter of the cloud reached a value of about 1 billion light-years, the interaction between the atoms and anti-atoms already became so frequent that the temperature of the cloud increased and it was transformed to an extremely large mass of ionized particles, biplasm. The term "biplasm" signifies that the plasmic mass contained ordinary ions and those obtained from anti-atoms. The violent reactions of the interaction of both kinds of ions was accompanied by the release of an enormous amount of energy and powerful radiation. The radiation pressure gave rise to forces which strove to expand the cloud.

On expanding, as a result of causes still not fully ascertained (among them an important role is played by magnetic forces), the biplasm cloud separated into two clouds: one consisting of ordinary ions and atoms, which subsequently became our world, and another one consisting of anti-atoms and anti-molecules, the mysterious anti-world about which we know

nothing as yet. It is possible that between these worlds there is some kind of transitional zone in which interaction between particles and their antipodes takes place. Sources of powerful radiation must appear in the intermediate zone, indicating that destruction of particles and anti-particles occurs there. Astronomy knows and has registered sources of very strong radiation far from our galaxy, the origin and nature of which remain unexplained. It is hard to assert with certainty whether the combustion of matter and anti-matter occurs there, but there are, in principle, no grounds for rejecting this hypothesis.

Primary Synthesis of Organic Compounds

1. PHYSICAL FACTORS WHICH AFFECT SYNTHESIS

However great the role of nuclear reactions in the general chemical activity in outer space, at low temperatures, nuclear processes are discontinued and are replaced by atomic and molecular reactions. Atoms finding themselves in cold regions of space put on their electron "overcoats", i.e., recover their lost electron shells and acquire the ability of combining with each other to form molecules. There is no doubt that ordinary chemical reactions, in all their diversity, are continuously taking place in celestial bodies and in the interstellar medium.

The analysis of carbonaceous chondrites disclosed the presence of various organic compounds which were formed in outer space.

Radiation could be the factor responsible for the origination of rather complex molecules from atoms, ions and radicals. Outer space is permeated by all kinds of radiation. This includes streams of protons and electrons; radiation of ultraviolet and γ -ray quanta; emission of neutrinos, heavy ions, etc. All these emissions can, to a greater or smaller degree, be the cause of ordinary and nuclear chemical reactions. Unfortunately, most frequently it is not known in what way the synthesis of organic compounds proceeds in the meteorites and asteroids wandering in space for

millions of years. The only way to solve the problem is to attempt to simulate certain processes, i.e., to expose the supposed initial substance to some particular radiation and to see what will come of it — just what compounds are formed in the model system. This method, in spite of its shortcomings (the short duration of exposure to radiation as compared to the cosmic period of irradiation) turned out to be very promising. Of special interest are the results obtained on simulating the processes in the Earth's atmosphere.

It should be pointed out, first of all, that the powerful corpuscular emissions (e.g., streams of protons) characteristic of cosmic rays induce nuclear reactions; they are too strong the "delicate" chemical reactions. It is the Earth's atmosphere that bears the force of the high-energy cosmic particles, and their energy is dissipated on piercing through the armour of air. Ultraviolet radiation is an important factor of chemical synthesis in the lower layers of the atmosphere. Other factors are atmospheric electric discharges, i.e., local currents of electrons and ions of short duration. The radioactive decay of elements that are present in the Earth's crust also plays a part, although generally a considerably smaller one; certainly the temperature indirectly associated with processes of decay of radioactive substances is very important for the synthesis of organic compounds.

We'll confine ourselves to a review of the results of experiments designed to ascertain just what organic compounds could have been produced on the Earth in those far-distant times when there was not as yet any life on it, i.e., approximately 2.5 billion years ago.

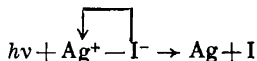
First of all we must familiarize ourselves with the general laws of the effect of light on matter.

2. ACTION OF LIGHT ON MATTER

The effect of light on matter is constantly observed by us. Our skin grows darker when exposed to the Sun (gets sunburned or tanned); the prolonged action of sunlight causes many colours to fade; the wonderful process of photosynthesis takes place in plants under the action of sunlight. Chemists know chemical processes the rate of which changes sharply due to the action of light. In photographing, the products resulting from the reduction of silver halides appear on the photographic plate in hundredths of a second; a mixture of chlorine and hydrogen reacts very slowly in the dark, but if it is exposed to a ray of sunlight for just one moment, an explosion of great force occurs.

Even a superficial knowledge of the principal laws of atomic physics is enough to understand the processes that occur in the branch of science known as photochemistry, i.e., the science that studies the reactions of light and matter. Light as has been noted above has a dual nature: sometimes it behaves like a wave and sometimes like a particle (a quantum or photon). Not only the photon, but all atomic particles, in general, have a dual wave-particle nature; under certain conditions they exhibit effects explicable only as wave phenomena. Nevertheless, usually a distinction is made between the interaction of matter and electromagnetic waves (visible light, ultraviolet rays, infra-red rays) and the interaction of matter and atomic particles (electrons, protons, α -particles and the high-energy γ -quanta). The term "photochemistry" in this case refers to the action of electromagnetic waves, whereas processes involving particles (corpuscular radiation) are studied in radiation chemistry. In the conditions of outer space both photochemical and radiation processes occur, and therefore we must become familiar with both types of reactions.

An electron orbiting a nucleus in the ground state can, on absorbing a quantum of energy, either pass to an excited orbit farther from the nucleus or escape from the atom. Which of the above two things will occur in a given case depends on the magnitude of the quantum of energy. If the quantum is great enough to cause the electron to escape from the atom, ionization will take place. Ionization and excitation are the most important results of the collision of a photon and an atom. In the general case, not all of a given quantum may be absorbed; then as a result of ionization, there will appear an ion, electron and a quantum of less energy (the Compton effect). This occurs, however, only at very high quantum energies (0.1-1 MeV); at low energies only excitation or ejection of electrons occur. Thus, when light, for example, acts on the silver iodide contained in the light-sensitive coating of a photographic plate or film, the electron in the iodine ion leaves its host (iodine) and is transferred to the silver ion:

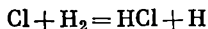


The resulting silver atoms form small accumulations on which metallic silver will be deposited in the process of subsequent treatment with a developer, thus producing the negative image.

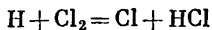
A light quantum making its way into a mixture of hydrogen and chlorine photoexcites the chlorine molecule as a result of which the bond between the two chlorine atoms in the Cl_2 molecule is broken and active Cl atoms having free (unpaired) electrons appear:



It is these atoms that on reacting with hydrogen molecules produce active hydrogen atoms:



Then the following reaction takes place:



and chlorine atoms reappear, sustaining a rapid chain reaction which results in an explosion of the whole mixture.

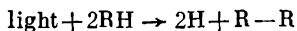
Subsequently, the chain process proceeds by itself, independent of the primary event which consists in the absorption of one quantum by one chlorine molecule; the subsequent process is a secondary one.

According to Einstein's law, one absorbed quantum causes the conversion of one molecule. In complex molecules, light sometimes not only causes an electron to pass to an excited state but also changes its spin (i.e., causes a change in the direction of the angular momentum which is associated with the rotation of the electron on its own axis). As a result, a molecule is obtained with two electrons, one of which is in the excited state, the other in the ground state, but both having the same spin. Two electrons with the identical spins cannot occupy one and the same orbit (Pauli exclusion principle) and, therefore, such a molecule remains in the excited state for a long time because the electron cannot return from the excited state to the ground state. This state is called the triplet state; it is characterized by high chemical activity.

At the low temperatures on the surface of planets, in particular, of the Earth, complex organic molecules began to originate; they were constantly exposed to solar radiation, and the chemical evolution which led to the appearance of life on the Earth was undoubtedly associated with the formation of excited triplet states.

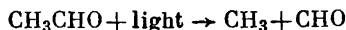
Under certain conditions light is capable of uniting relatively simple molecules to form more complex ones. Thus, light can form one molecule from two molecules denoted as RN (where R is a hydrocarbon radical) by

combining two radicals:

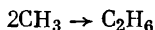
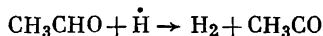
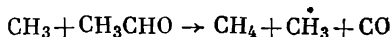
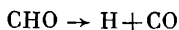


In this reaction hydrogen generally combines with atmospheric oxygen to form water:

On the other hand, light often decomposes molecules. Light quanta, for instance, dissociate acetaldehyde molecules into two radicals (groups with unpaired electrons):



Then follows a process as a result of which a chain reaction is developed:



When analyzing the probable composition of the atmospheres of planets and the formation of certain carbon compounds in meteorites, the various reactions into which organic compounds enter when being exposed to the action of light must be taken into account. Light participates especially vigorously in processes of oxidation by oxygen; in these reactions peroxides and hydroperoxides (containing the characteristic — O — O — groups) are obtained, which promote the development of oxidizing chain reactions. Light can also induce hydrolytic dissociation (the transformation of amino acids to hydroxy acids), the reconstruction of the skeleton of a molecule, reactions in which addition to double bonds occurs, etc.

Thus, we see that the streams of light quanta sent by the Sun and other stars are powerful means of influencing chemical reactions. When discussing the effect of light on matter in the period when the Earth

was young and there was still no life on it, it is essential to ascertain the role of photochemical reactions in the processes of origination of the organic compounds which were later involved in the life cycle. There are no molecules that are more complex and more finely organized than those which are the basis of life. When regarding inanimate nature, the first impression formed on looking around us is that there are few carbon compounds present and those that do occur — carbon dioxide, hydrocarbons (petroleum, petrol, kerosene, polyethylene) — do not resemble proteins or amino acids. Perhaps in some distant period of the Earth, there was an abundance of proteins and all that was necessary for life on its surface and then for some reason or other they disappeared. This hypothesis is beneath criticism. There are no grounds for believing that complex fragments which form cells were produced by some process and then combined at once in such a way that a system capable of living was obtained.

On the other hand, however, observations and experimental data afford evidence in favour of the hypothesis that molecules gradually became more and more complex; as a result of this process, some primary forms of life were produced, perhaps not very similar to present-day forms. However, there is no doubt that the basic chemical transformations in these prototypes of future organisms were the same as those in contemporary ones.

The material from which molecules of biological value were built did actually exist in abundance on the Earth. The impression that nature is poor in organic compounds is not altogether true.

A. Oparin was the first to state with certainty that the process of conversion of simple compounds to compounds of biological value was a process of gradual evolution; somewhat later the same opinion was expres-

sed by D. Holdane. In our days the overwhelming majority of biochemists and biologists share this point of view. It has been proved that the most important compounds required for sustaining and developing life could be produced on the Earth as a result of diverse reactions. The reactions which initiated the long chain of transformations creating the conditions on the Earth for the appearance of the first forms of life proceeded comparatively readily. Light is not the only source of energy that stimulated these reactions.

3. RELATIVE ROLE OF VARIOUS ENERGY SOURCES IN SYNTHESIS OF PRIMARY ORGANIC COMPOUNDS

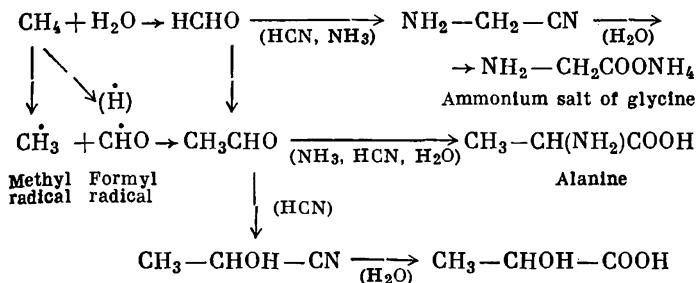
In order to estimate the relative role of various energy sources of importance in primary chemical evolution on the Earth, M. Calvin calculated the average quantity of energy obtained by the Earth's surface each year from various processes. It was found, for example, that as the result of volcanic activity the Earth receives about 0.04×10^{20} cal/year; lightnings give 0.05×10^{20} cal/year; at the present time the decay of radioactive potassium provides 0.3×10^{20} cal/year (2.6 billion years ago this process yielded 4 times as much energy); ultraviolet radiation (of a wavelength less than 200 nm) brings 4.58×10^{20} cal/year. M. Calvin also pointed out the part that might be played by impacts of meteorites which are a source of energy acting from the beginning of the Earth's existence and which give about 0.5×10^{20} cal/year. These figures show that the greatest role in the generation of energy is played by ultraviolet radiation.

Neither should radioactive decay be overlooked; such radiation in the prebiological period must have occupied the second place after ultraviolet radiation.

Since 1950 a fairly large number of simulated experiments have been performed. Scientists, simulating the Earth's atmosphere as it existed in distant geological periods, exposed a chosen mixture to the action of various factors. In 1950, Calvin and his co-workers exposed a mixture containing water and carbon dioxide to the action of a stream of helium ions of an energy equal to 40 MeV in a cyclotron under a partial pressure of CO_2 equal to 2.4-2.9 mm Hg. Bivalent iron ions were added to the solution being irradiated. After irradiation formic acid and formaldehyde were found in the solution.

In 1952, S. Miller studied the effect of radiation on a mixture containing methane, ammonia, water and hydrogen; later in 1953, he investigated the action of electrical discharges on similar mixtures. In his layout a stream of water vapours passed continuously between two electrodes. The resulting slightly volatile compounds were condensed together with steam in a reflux condenser, and the concentration of the reaction products gradually increased in the mixture in the flask. The test lasted for a long time, a whole week, but on a geological scale this period of time can be considered to be a moment. And in such a "moment", an appreciable amount of hydrogen cyanide, aldehydes and amino acids was formed in the mixture. Alanine, glycine, β -alanine, aspartic acid, aminobutyric acid, formic acid, acetic acid and other compounds were found in the mixture. As the experiment proceeded, the concentration of ammonia decreased while that of HCN at first increased. As the concentration of the amino acids grew, that of HCN began to fall gradually and in 160 hours already approached zero. The amount of aldehydes reached a maximum in 75 hours; then aldehydes began to disappear gradually.

The sequence of reactions in the synthesis of amino and hydroxy acids, according to Miller, is as follows:



An important part in these reactions, as is seen, is played by formaldehyde and hydrogen cyanide. Attention should also be paid to the part played by methyl and formyl radicals, active groups with unpaired electrons. The hydrogen atoms (H) are also radicals which combine to form H_2 molecules.

M. Calvin believes that among the primary components of the Earth's atmosphere in the prebiological period, those that should be named first are water (in the form of vapours), the oxides of carbon (CO and CO_2), hydrogen, methane and ammonia. It was from these components that the more complex molecules were formed: hydrogen cyanide, HCN ; dicyanamide, HNCN_2 ; formic acid, HCOOH ; formaldehyde, HCHO ; glycolaldehyde, $\text{CH}_2\text{OH}-\text{CHO}$; and acetic acid, CH_3COOH .

Subsequently, the composition of molecules became more complex and there appeared succinic acid, $\text{HOOC}(\text{CH}_2)_2\text{COOH}$, and the amino acids: glycine, $\text{CH}_2(\text{NH}_2)\text{COOH}$; alanine, $\text{CH}_3\text{CH}(\text{NH}_2)\text{COOH}$; aspartic acid, $\text{HOOC}-\text{CH}_2-\text{CH}(\text{NH}_2)\text{COOH}$ and hydroxy acids.

P. Eeibelson studied various mixtures of nitrogen and hydrogen, carbon dioxide, water vapours, carbon

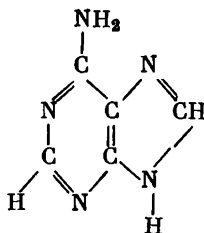
monoxide, ammonia and found amino acids in the reaction products. The Soviet scientists A. Pasynsky and his co-workers and also N. Dodonov and A. Sidorova and others showed that ultraviolet radiation is the factor that could have caused the formation of amino acids from such substances as ammonia, water, formaldehyde, ethane, etc. It has been established by the Indian scientist K. Bakhadur that molybdenum oxide acts as a catalyzer in the formation of amino acids from water, nitrogen and paraformaldehyde. O. Shmeleva, T. Petrova and L. Nikolaev found that ferric hydroxide can catalyze the reaction of the formation of amino acids under similar conditions. It is known that other factors (X-rays, ionizing irradiation, ultrasonic vibration and even heating) also favour the formation of amino acids.

When ascertaining the part played by corpuscular radiation in the synthesis of primary compounds, M. Calvin exposed a mixture containing ammonia, methane and hydrogen (the latter taken in excess) to electron bombardment. Something like that could have occurred in ancient times when the source of electrons in the Earth's crust was the potassium isotope of atomic mass 40. In the experiments carried out by M. Calvin and his collaborators, a great number of diverse and rather complex compounds were obtained, among which were adenine, aspartic acid, glycine, lactic acid and derivatives of imidazole. Thus, it was firmly established that amino acids are not rare substances; on the contrary, they are readily formed as a result of a great variety of reactions that occurred in prebiological times. Nature created forms of life not from unusual, rare materials but from those that were frequently formed as a result of natural processes.

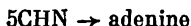
Amino acids and hydroxy acids are not, by far, the only organic compounds that occur in a great vari-

ety in nature, primarily in the tissues of animals and plants. How did molecules of complex cyclic structure and containing specific combinations of nitrogen, phosphorus and carbon compounds come to be formed? Some of them, for instance, nucleic acids, which play an important part in protein synthesis, appear to be of an unusually intricate structure. They are very large molecules in which units consisting of carbohydrate residues and phosphoric acid radicals are combined with a purine or pyrimidine base (adenine, cytosine, guanine, uracil). How did all this originate "by itself"? Direct simulated experiments have shown that simplicity and complexity are very relative concepts. Sometimes very complex molecules are formed under comparatively simple conditions which are easily attained.

The synthesis of adenine, a purine derivative, can illustrate this:



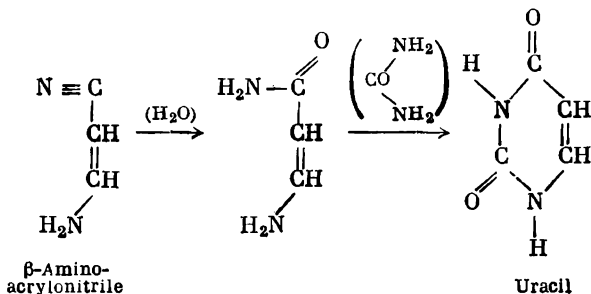
It was found that this compound can be formed from hydrogen cyanide:



The scientist Oro studied this type of synthesis in great detail and proposed a scheme in which ammonia and hydrocyanic acid react to form the intermediate compound acrylonitrile, $\text{N} \equiv \text{C} - \text{CH} = \text{CH} - \text{NH}_2$. The amount of hydrocyanic acid and ammonia present

in the Earth's atmosphere in the prebiological period was great enough and, consequently, the origin of adenine and similar compounds on the Earth's surface was quite possible.

Other compounds of equal importance are the derivatives of pyrimidine. These compounds also have cyclic molecules and each cycle contains two nitrogen atoms in the meta position. The derivatives of pyrimidine include thymine, cytosine, uracil and their derivatives. Pyrimidine bases could, apparently, be formed from aminoacrylonitrile (or its derivatives), water or ammonia and urea, $\text{CO}(\text{NH}_2)_2$. Aminoacrylonitrile, as stated above, is synthesized from ammonia and hydrocyanic acid. Urea is obtained from carbon dioxide and ammonia. Oro presumed that uracil could be formed from these substances according to the following scheme:



Purines and pyrimidines absorb light of wavelengths of about 2600 Å; according to data obtained, such radiation could have penetrated through the primary atmosphere of the Earth, and, consequently, must have had some effect on the resulting purine and pyrimidine molecules. The absorption of light frequently does not cause molecules to disintegrate but rather excites them; the molecules become more active and

enter more readily into various reactions. Hence, organic bases will be more reactive when exposed to light. It is worthwhile to ascertain, for example, what compounds are obtained from purine in solutions containing, besides purine, other substances with which purines are combined in living organisms.

Nucleic acids contain compounds consisting of an organic base, carbohydrate and phosphate. These compounds are called nucleotides. For instance, a compound consisting of the base adenine, ribose and phosphate is called "adenosine-nucleotide".

At first sight it seems hardly probable that such a compound could, by itself, be formed from simple compounds. However, experiments performed by the scientists Sagan, Ponamperuma and Mariner have shown that on exposing a mixture of phosphate, adenine and ribose to light a nucleotide is actually formed. Merely exposure to ultraviolet rays, which of course were quite plentiful in the prebiological period, was sufficient to induce the formation of very complex molecules!

As concerns adenine, this compound is also formed from comparatively simple molecules.

The problem of the origin of carbohydrates needed to obtain nucleotides is likewise solved simply. It has been proved that in alkaline solutions of formaldehyde 30 different kinds of carbohydrates are formed under the catalytic action of alkalis and oxides of metals. Phosphates are widespread in the Earth's crust (in minerals, soil and water). Hence, all the constituents of nucleic acids (base, carbohydrate, phosphate) could easily have been formed and then combined in the proper way under the conditions that prevailed on the Earth before the appearance of life on it.

Of special interest is the question concerning the conditions under which the first proteins were formed.

S. Fox came to the conclusion that amino acids, under the influence of various factors, could have been converted to polypeptides in heated volcanic soils and in this way might have initiated the synthesis of protein-like substances. In order to verify these assumptions S. Fox and his collaborators heated a mixture of dry amino acids in a suitable vessel (this was simply a piece of lava with a small depression in it) in an oven where a temperature of 170°C was maintained. In a few hours the mixture of amino acids was transformed into a viscous mass of the colour of amber. After that a 1 per cent hot sodium chloride solution was poured on the lava and the resulting polymer.

On analyzing the solution it was found that it contained a great number of spherical particles (microspheres) consisting of products of condensation of amino acids, i.e., of a substance similar to proteins (Fig. 27). The protein-like substance consisted of 18 amino acids (sometimes fewer) and was called a *proteinoid* — which means resembling a protein. When carrying out the reaction in a polyphosphoric acid solution at the relatively low temperature of 100°C during 150 hours, S. Fox obtained a proteinoid which differed in composition from that of the initial mixture: it consisted of 33 per cent aspartic acid, 17 per cent glutamic acid, and 3 per cent each of other amino acids. S. Fox came to the conclusion that proteinoid molecules are formed from amino acids not as the result of chance combinations but in accordance with certain selective principles.

Proteinoids aroused great interest and were carefully studied. It was found that they are capable of forming membranes and sacs (pouch-like cavities), and that individual microspheres united to form chains and more complex compounds. It is the opinion of S. Fox that the zones of volcanic activity could have

been the site of primary synthesis of proteinoids. Rains washed these compounds away and carried them to

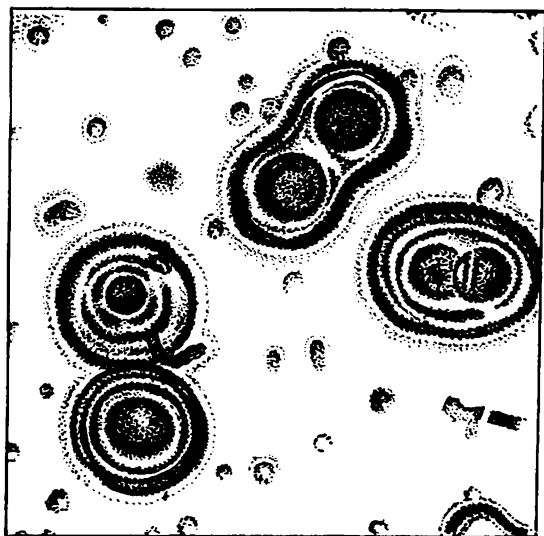


Fig. 27. Photograph of proteinoids (from a paper by S. Fox)

shallow rivers or seas where, in all probability, the subsequent processes of formation of more complex proteionoid structures took place.

Recently, M. Calvin has analyzed in detail a number of probable reactions that might have led to the formation of various biologically active substances. He emphasized, in particular, the role of autocatalytic processes responsible, for example, for the production of hemoglobin, in which heme acts as the catalyzer in the oxidation of the initial substances.

4. PRINCIPAL TYPES OF CHEMICAL PROCESSES IN SPACE

A résumé of the characteristic transformations of matter in space shows that different processes develop in it, depending on the temperature and pressure. On comparing the reactions which occur at very high degrees of compression and extremely high kinetic energies of particles with those that occur at low temperatures and densities, the following most important types of processes can be distinguished.

1. Pressures equal billions of atmospheres. Densities reach 10^{15} - 10^{16} g/cm³ (according to V. Ambartsumyan and G. Saakyan). Nucleons react with each other; the cores of nucleons are pressed to one another. Mesons and hyperons appear, resulting in the origination of hyperon stars; particle — anti-particle pairs may appear (according to D. Frank-Kamenetsky). The hyperon stars can explode scattering matter over great areas.

2. Densities equal 10^{12} - 10^{15} g/cm³. Protons are converted to neutrons. Neutron stars appear. (An explosion resulting in the formation of a neutron star was observed in 1954-1958 and registered in the Mount Palomar observatory.)

3. Densities equal 10^6 - 10^{10} g/cm³. Such are the densities in white dwarfs. All the atoms are "crushed" and an electron gas surrounds the atomic nuclei. The gravitational forces are balanced by the pressure of the electron gas.

In some respects, these conditions are similar to those supposed to exist in the centre of the planet Jupiter, where metallized hydrogen is probably found. In general, the loss of electrons by atoms and the formation of a common electron cloud is characteristic of the metallic state. Very high temperatures correspond to these

very great pressures. That is why no molecules in the ordinary sense of this word are formed under such conditions.

4. Densities are of the order of 10 g/cm^3 . This is the density of matter¹ on the planets. At low temperatures a great variety of compounds can be formed. The density of matter¹ on the Sun is, on the average, about 1.4 g/cm^3 . At high temperatures only the simplest combinations of atoms — radicals of the type of CN, C_2 , C_3 or molecules of stable oxides (TiO_2) — can exist. Ions are readily formed, and the atoms lose not only their outer electrons but part of the inner ones as well.

5. Densities are very low. Such are the densities of interstellar matter. Ions exist in it for a long time; the speed with which they move is often very great (their motion is accelerated by the magnetic fields of celestial bodies). When they collide, nuclear reactions can occur. On the other hand, at low temperatures, the action of radiation and high-energy particles can result in the synthesis of complex molecules including various organic compounds. Solidified synthesis products, for example, form the ices contained in the nuclei of comets.

At high temperatures and low densities (e.g., in the surface gases of stars and in the red giants) the atoms are, to a great extent, ionized; radicals of a simple structure are also formed.

6. Moderate densities ($1\text{--}10 \text{ g/cm}^3$) and temperatures (from -80 to $+55^\circ \text{C}$) prevail. If there is adequate protection against powerful cosmic rays, a successive chain of reactions is developed, resulting in the formation of organic molecules which finally become the constituents of self-regulating systems. The life of these systems is not only maintained by various sub-

¹ In the centre it is about 100 g/cm^3 .

stances found in their surroundings, but the systems are reproduced so that their mass and number will increase. For unknown reasons, processes set in which make the systems more complex although their chemical composition remains almost unchanged. The systems assume mechanical functions, their recombination mechanism is perfected, they adapt themselves better to their environment and they themselves even alter it. It is, of course, the origin of life on Earth that is spoken of here. The problems of chemistry are closely interwoven here with those of biology. One of the most interesting problems posed before man is to ascertain the scope of and the laws governing biological phenomena in space.

But meanwhile... space chemistry is taking its first steps. It would have been impossible to understand the physical nature of the processes characteristic of outer space if "Earth" physics and chemistry had not afforded potent means of theoretical research and apparatus which have made it possible to penetrate into the depths of time and space. Rapid and unprecedented progress awaits this science in the nearest future.

INDEX

- Accelerators, 143, 169
- Achondrites, 37, 40
- Alpha particles, 132, 135, 137, 143, 164, 168
- Amino acids, 31, 34, 46, 180, 183, 184, 188
- Antimatter, 170-172
- Anti-particles
 - anti-meson, 170
 - anti-neutrino, 131, 170
 - anti-proton, 170
 - positron, 133, 170
- Appolo, 10, 12
- Asteroids, 52, 53, 174
 - chondrite, 66
- Astronomy, 21, 53, 123, 151, 169, 173
 - radioastronomy, 120
- Astrophysics, 10, 21, 53, 76, 125
- Atmospheres, *see* under names of planets
- Atom
 - size of, 129
 - states of,
 - excited, 17, 18, 137, 178
 - ground, 17, 178
 - transition of, 22
- Atomic nucleus, 132, 133, 135
 - constituents of, 129-132
- Atomic number, 131, 152
- Atomic physics, 16-17, 170
- Beta particles, 131
- Bohr's theory, 16
- Bolometer, 33-34
- Boyle's law, 99
- Brightness, 107-108
- Carbon scale, 130
- Catalyzer, 101, 184, 189
- Celestial bodies, analysis of
 - direct chemical, 12
 - radio-wave, 21-22
 - spectral, 15
 - see also* Comets, Meteorites, Planets, Stars
- Chemical elements in space
 - abundance of, 154-155
 - synthesis of
 - cold, 161
 - hot, 160
- Chemical processes in space, 11, 94-106, 129
 - principal types of, 190-192
 - nuclear, 174
 - ordinary, 174
- Chemical reactions
 - equilibrium of, 61-62
 - nuclear, 99, 105, 132, 138, 154
 - in stars, 162-166
 - ordinary, 99, 106, 132, 138, 153

radioactive, 137
 work of, 61-62
 Chondrites, 37, 39, 40
 carbonaceous, 33, 34, 41-46,
 174
 Chondrules, 39
 Chromatography, 29-33, 43,
 46, 85
 Collapse, 156, 160
 Comets, 127-128
 coma, 128
 core (nucleus), 128, 191
 head, 128
 ices, 128, 191
 radicals in, 128
 tail, 127
 Compton effect, 177
 Computers, 63-65
 Constellations
 Andromeda, 159
 Coma Berenices, 159
 Hercules, 159
 Orion, 153
 Sagittarius, 117
 Scorpio, 123
 Cosmic
 dust, 24, 42, 167
 matter on Earth, 24
 rays, 39, 73, 74, 168
 Cosmology, 72, 169-173
 Coulomb barrier, 136

 De Broglie, 17
 Deuterium, 42, 139, 147, 160,
 169
 Deuteron, 135, 139, 142
 Dielectric constant, 22
 Doppler effect, 21, 122
 Dwarfs, 94
 subdwarfs, 109, 115, 116, 125
 white, 109, 124, 190
 yellow, 156
 Earth, 68-77
 atmosphere, 68, 69, 70, 77

chemosphere, 70
 hydrosphere, 69, 74, 76
 lithosphere, 69, 74
 crust, 74, 75, 76
 mantle, 74
 life, origin and evolution
 of, 68, 71, 192
 Earthquakes, 77
 Effect
 energy, 105, 138
 photo, 145
 thermo, 100-103
 Einstein's
 equation of mass-energy
 equivalence, 105, 137,
 146, 171
 law of photochemical equi-
 valence, 121, 178
 theory of relativity, 10
 Electric fields, 96, 132, 134
 Electron, 16, 163, 130, 131,
 134
 unpaired, 102, 177
 Electron shell, 174
 Elementary particles
 properties of, 132-134
 see under names of particles
 and also Anti-particles
 Energy,
 activation, 100, 135
 binding, 139, 140
 excitation, 140, 177
 kinetic, 138
 radiant, 107
 solar, 145-150
 sources, nuclear, 136-140

 Fluorometry, 35
 Forces
 gas pressure, 152
 gravitational, 25, 114, 122,
 152, 156

repulsive, 136
Fraunhofer lines, 13, 58

Galaxy, 73, 96, 107, 124

Hertzsprung-Russell diagram,
109-112
Hyperons, 190

Interplanetary stations, auto-
matic, 9
American
 Mariner, 83
 Pioneer, 12
 Surveyor, 10
future, 9
Soviet
 Luna, 12, 13, 78
 Mars, 12, 13, 82
 Venera, 12, 64, 67

Interstellar matter, 11, 53,
166-167
Ionization, 103, 130, 177
Isotopes, 36, 48, 73, 74, 76,
149, 160, 161

Jupiter, 12, 15, 25, 66, 86,
87-93

Kirchhoff, 13
Kont, 14

Life on Earth and other
planets, 84, 89, 192

Light
 dual nature, 16, 121, 122
 effect on matter, 176-181
 infrared, 17
 pressure, 120-122, 124

radiation of, 18
ultraviolet, 17
visible, 17
Luminosity, 108, 109
Lunar soil samples, *see* Moon

Magnetic fields, 7, 96, 114, 132
Magnitude, absolute, 107
Main sequence (of stars), 111
Mars, 15, 25, 66, 80, 82-86
 life on, 68, 84-86
Mass defect, 146
Mass-energy equivalence, *see*
 Einstein's equation
Mass number, 152
Matter in outer space
 effect of high pressure, 97-
 99
 effect of high temperature,
 100-103
 origin, 170
 plasmic state of, 103-106
Megatherium, 27
Mendeleev's periodic system,
131
Mercury, 66, 67
Mesons, 134, 190
Metallic state, 190
Meteorites, 12, 37-53
 abundance of elements in,
 41
 age, 39, 48
 analysis of, 29-31
 composition, 37, 43
 diamonds in, 30-32
 cosmic origin of, 26
 craters
 Arizona (Canyon Diablo),
 27, 51
 Sikhote-Alin, 28
 occurrence, 25, 27, 28, 37,
 49-51
 properties, magnetic, 37
 showers, 27

- swarm, 25
- types, 25, 37
- Model (simulated) experiments, 45, 82, 85, 86, 89, 124, 159, 168, 175, 182, 184, 185, 187, 188
- Molecular mass, 152
- Momentum
 - angular, 22
 - photon, 122
- Moon, 66, 77, 82
 - soil samples from, 10, 12, 15, 36, 78-81
 - anorthosites, 79
 - apparatus for analyzing, 36
 - regolith, 78, 80
- Nebula, 15, 53, 124
 - Andromeda, 153
 - Archer (A, B2), 166
 - Crab, 126, 157
 - Horsehead, 153, 154
- Neptune, 66, 86-88, 90
- Neutrino, 131-133
- Neutron, 131, 141
 - capture of, 136, 148, 160
- Newton's law, 121
- Novae, 123-126
- Nuclear reactions, 97, 135-136
 - denotation of, 144
 - energy sources, 136-140
 - in cyclotrons, 159
 - types, 140-145
 - induced by α -particles, 143
 - induced by deuterons, 142, 143
 - induced by neutrons, 141
 - induced by protons, 141-142
 - photonuclear, 143
- Nucleic acid, 187
- Nucleons, 131, 136, 143, 190
- Nucleotides, 187
- Nucleus
 - atomic, *see* above
 - comet, 128
 - compound, 136, 140
 - states, 136
 - stellar, 153
 - target, 135, 136
 - denotation of, 140
- Observatory
 - flying, 8
 - Palomar, 190
- Orbit, 16, 17
- Orbital, 17
- Organic compound in outer space, 168-169
 - primary synthesis, 174-189
 - energy sources, 187-189
 - factors affecting, 174-175
 - on Jupiter, 89
 - on Mars, 84
 - simulated synthesis, 168
- Pauli exclusion principle, 178
- Photochemistry, 176-181
 - photochemical reactions, 176
 - radiation processes, 176
- Photons, 16, 121, 134, 145, 171, 177
- Planck's formula, 16, 18, 121
- Planets, 65-93
 - atmospheres of, 60-65
 - inner and outer, 66
 - origin, 42, 48, 53-56
 - see* under names of planets
- Plasma, 19, 89, 103-106, 151, 161
 - biplasm, 172
 - simulation of plasma state, 121

Pluto, 66
 Positron, 131
 Pressure
 gas (electron), 152, 156, 190
 high, effect of, 97-99
 in stars, 156, 157
 light, 120-122, 124
 radiation, 156
 Proteinoids, 188, 189
 primary synthesis of, 189
 Proteins, 31, 46, 180, 187
 Proton, 131, 141
 Pulsating stars, 21, 157, 158, 159

Quanta, 16, 18, 136
 Quantum theory, 121, 182

Radiation
 corpuscular, 184
 infrared, 33
 relect, 45, 169
 solar, 13, 67, 70, 128, 168, 178
 ultraviolet, 17, 175
 visible light, 17, 33
 X-ray, 7, 23, 105, 159
 Radicals, 102, 169, 183, 191
 complex, 103
 in comets, 128
 Radioactive decay, 146, 175, 181
 Radioautography, 35, 85
 Radiolysis, 45
 Rays, *see* Radiation
 Research methods
 chemical, 29-33
 physicochemical, 33-36
 see Fluorometry, Radioautography, Spectrometry

Satellites, 125
 artificial Earth, 8, 24
 meteorological, 8
 of planets, *see* under names of planets
 Saturn, 66, 86, 87, 90
 Solar activity, 7, 70, 80
 Solar system, *see* Planets, Sun
 chemistry of, 53-56
 theory of origin, 53-54
 Spectra
 absorption, 19, 20, 33, 34
 emission, 15, 33, 35
 reflection, 15, 60, 82
 Spectroscopy, 7, 13, 19, 33-35, 65, 114, 124
 infrared, 7, 15, 18, 20, 43
 radio, 7, 21
 ultraviolet, 7, 15, 43
 Spin, 131, 178
 Spots
 Great Red Spot on Jupiter, 92
 Sun, 57
 Stars
 according to chemical composition, 112-120
 carbon, 117
 helium, 116
 hydrogen, 115
 iron, 114
 manganese, 114
 silicon, 114
 data for certain stars
 Alpha Centauri, 13, 107
 Aquila, 88
 Capella, 108
 Cygnus, 108
 Procyon, 153
 Sirius, 108
 Standard bearer, 108
 Sun, 108
 Swan, 159
 Vega, 153
 density, 94, 95

- life history of, 111-112, 120, 151-162
- mass of stellar matter, 152
- nuclear reactions in, 162-166
- number of, 107
- size of, 129
- sources of energy, 129, 136, 145
- spectra, 115
- temperature, 109, 112, 153, 155
- types
 - Cepheid, 107
 - Giants, 95, 107, 109, 112-117, 155, 160, 165
 - hyperon, 190
 - neutron, 157, 190
 - superdense, 159
 - Wolf-Rayet, 122-123
 - see also* Dwarfs
- Stellar classification, 109
- Stellar energy sources, 129, 136, 145
- Stellar evolution, *see* Stars
- Sun
 - atmosphere, 59-60
 - catalytic nuclear processes, cycles
 - neon-sodium, 149, 150
 - nitrogen-carbon, 148, 149
 - proton, 147, 148, 162
 - chromosphere, 58
 - composition, 59
 - corona, 59
 - photosphere, 57, 58
 - spots, 57
 - temperature, 109
- Supernovae, 73, 126-127, 160
- Technetium, 115, 118
- Temperature
 - high, effect of, 100-103
 - in stars, 153, 155
- Thermocouple, 18, 33, 65, 67
- Triplet state, 178
- Tritium, 73, 139, 140
- Triton, 139
- Universe
 - origin and evolution, 169-173
- Uranus, 66, 87, 90
- Venus, 15, 20, 64, 66, 67, 68
- Wavelengths, 33
- Waves
 - light, 17
 - radio, 93, 126
- Widmanstätten structure, 37



TO THE READER

Mir Publishers welcome your comments on the content, translation, and design of the book.

We would also be pleased to receive any suggestions you care to make about our future publications.

Our address is:

USSR, 129820, Moscow, I-110, GSP, Pervy Ritzhsky Pereulok, 2, Mir Publishers.

Printed in the Union of Soviet Socialist Republics

The textbook is designed for upper grade students of secondary schools. It contains information about the chemical composition of the planets of the solar system, meteorites, the Sun; about the synthesis of elements on the stars, the methods of studying space chemistry, as well as the catalytic nature of nuclear processes.

The author describes the behaviour of substances at very high and very low temperatures and pressures, considers the possibility of the formation of organic compounds in outer space and in the prebiological period on the Earth.